Stellar Temperatures

Since stars are not solid bodies, their “size” and “temperature” are somewhat ill-defined quantities. (The emergent flux from a star comes from different levels of the photosphere, which have different temperatures.) We define the “effective temperature” of a star is through the equation

$$L = 4\pi R^2 \sigma T_{\mathrm{eff}}^4$$

This is close to the $\tau = 2/3$ photospheric temperature; for this class, we will not make a distinction.

Stellar Spectral Energy Distributions

Stellar temperatures range from ~3000 K to ~100,000 K (although there are exceptions). To zeroth order, they can be considered blackbodies, with stellar absorption lines on top.

There is a great variety of stellar absorption lines; the strength of any individual line is determined by the star's

- Temperature (most important)
- Surface gravity
- Abundance

Historically, stellar spectral types have been classified using letters; the temperature sequence is (hot-to-cool) O-B-A-F-G-K-M-L-T-Y (with numerical subtypes). Orthogonally, stars are also defined in a "luminosity sequence" (which largely reflects size, and is hence a gravity sequence). These are roman numerals, V to I (high-to-low gravity).

Aside: F_λ versus F_ν

Flux density is quoted as either F_ν (flux per unit frequency) or F_λ (flux per unit wavelength). The two are not identical, but are related.

$$F_\lambda \, \mathrm{d}\lambda = F_\nu \, \mathrm{d}\nu$$

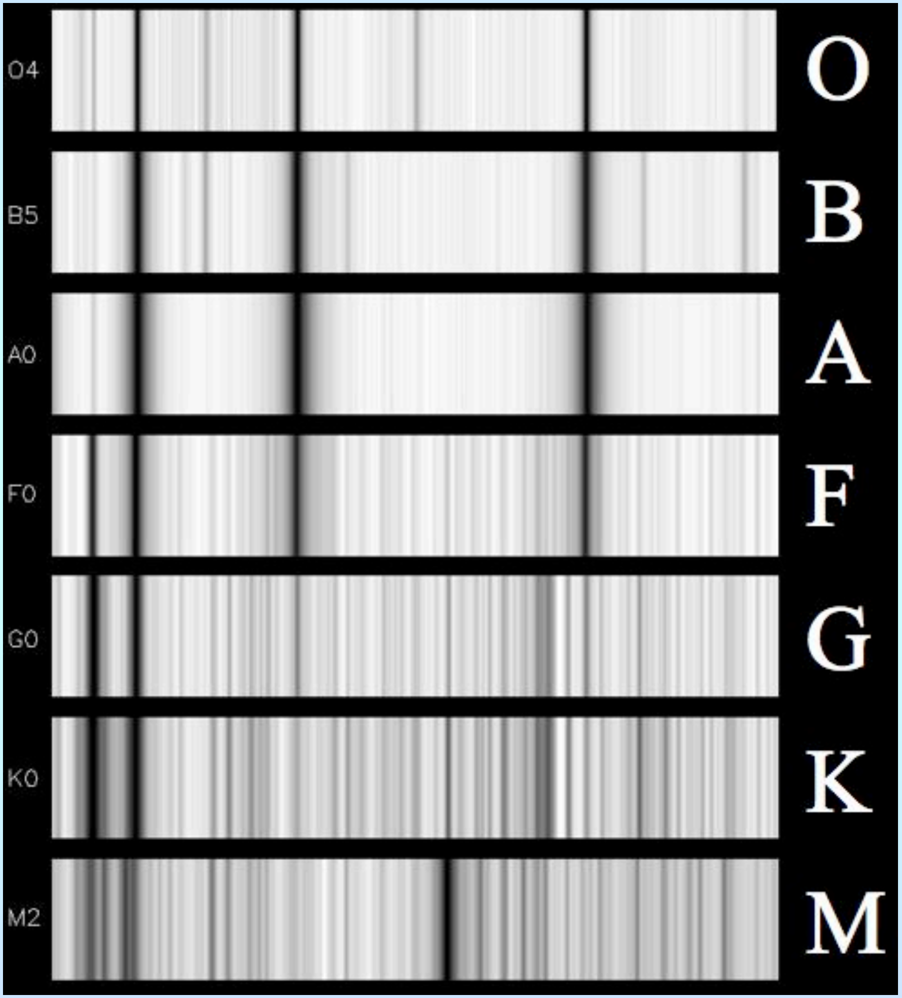
but

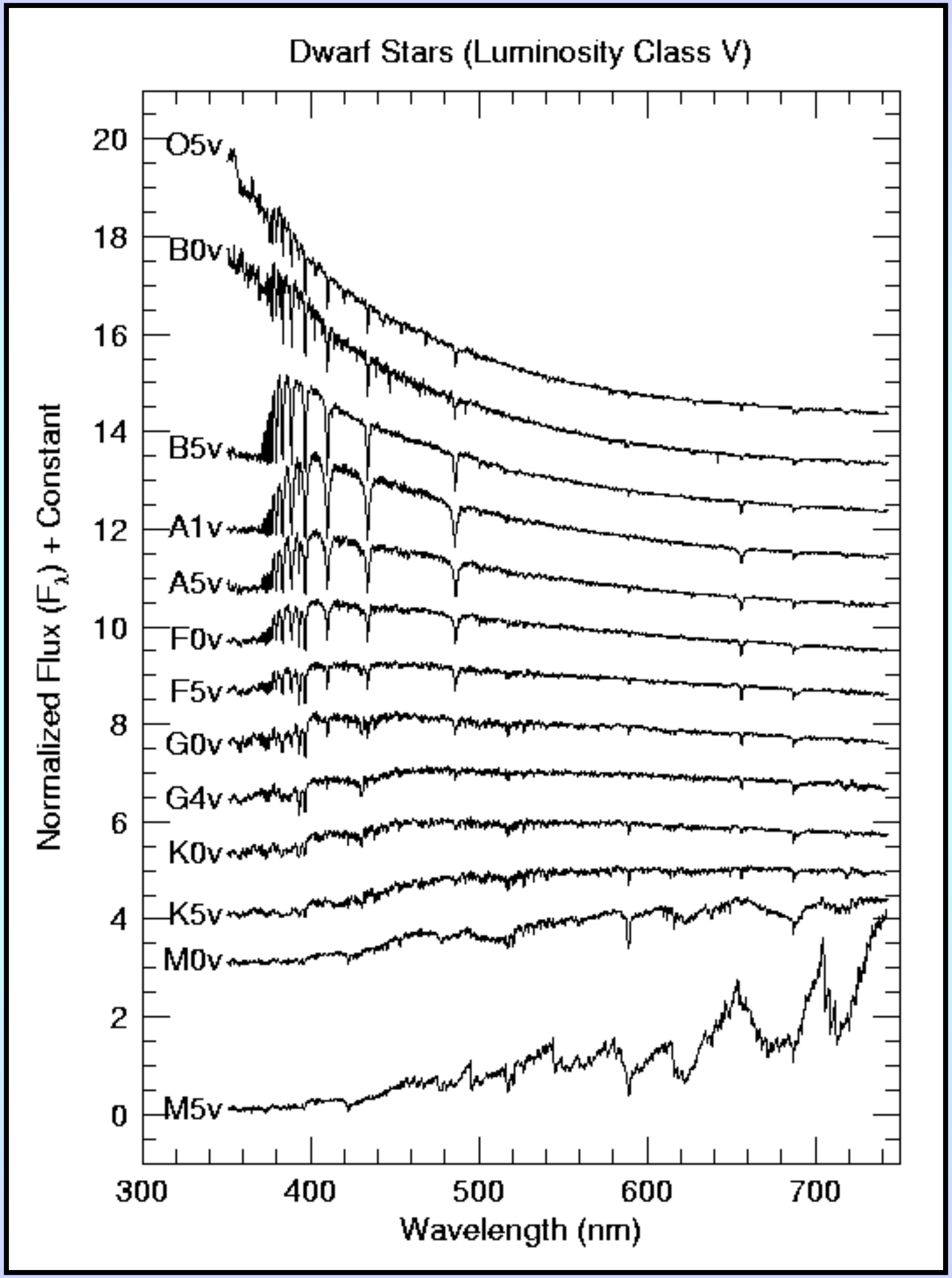
$$c = \nu\lambda \quad \Rightarrow \quad \nu = \frac{c}{\lambda} \quad \Rightarrow \quad d\nu = \frac{c}{\lambda^2} d\lambda$$

so

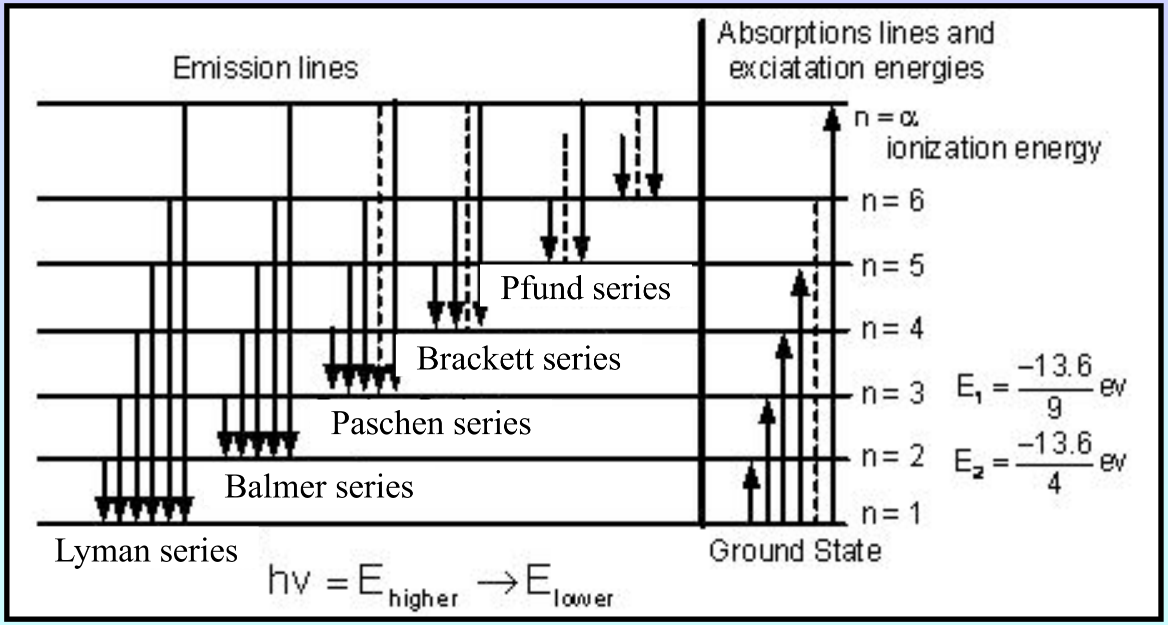
$$F_\lambda = F_\nu \frac{c}{\lambda^2}$$

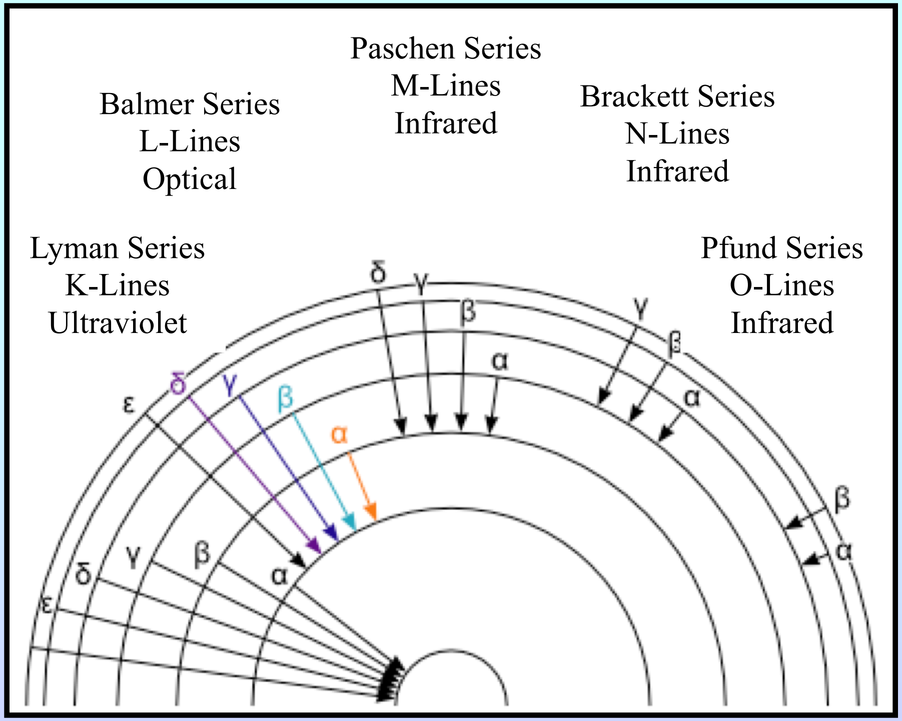
Stellar Spectral Types

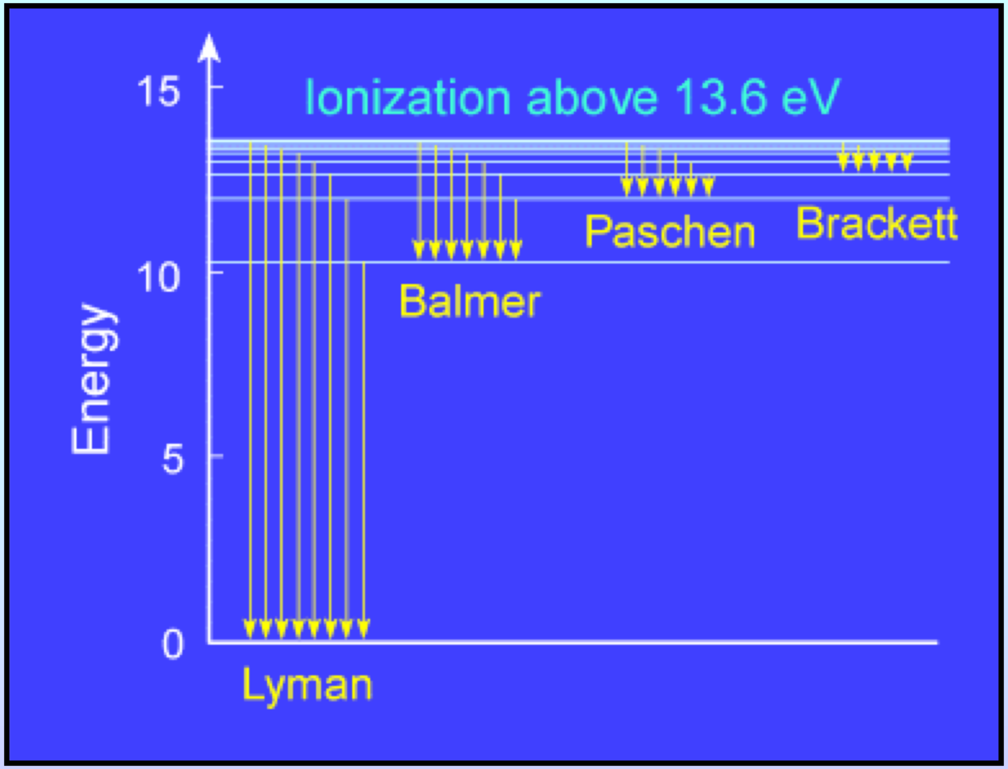




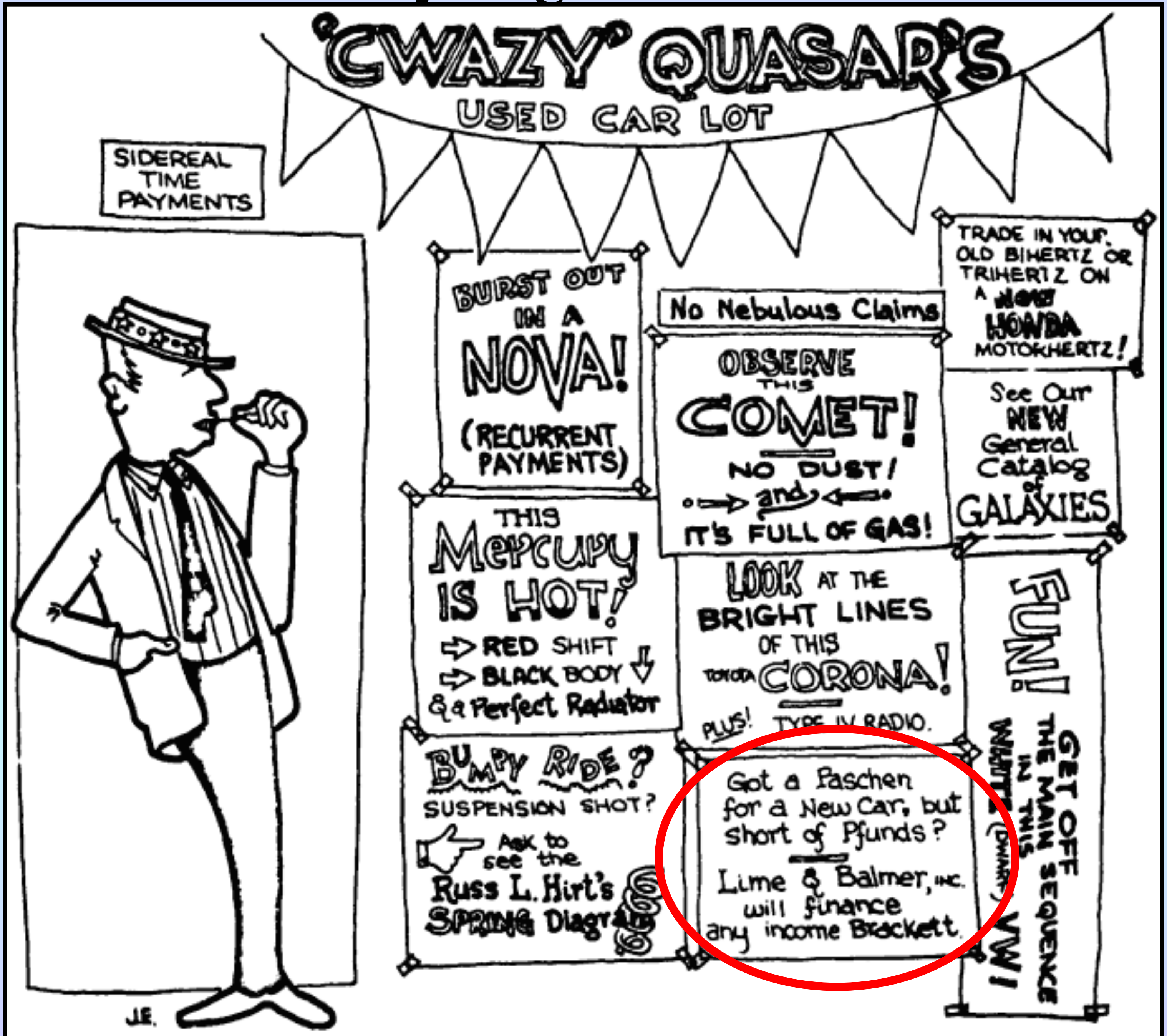
Hydrogen Lines



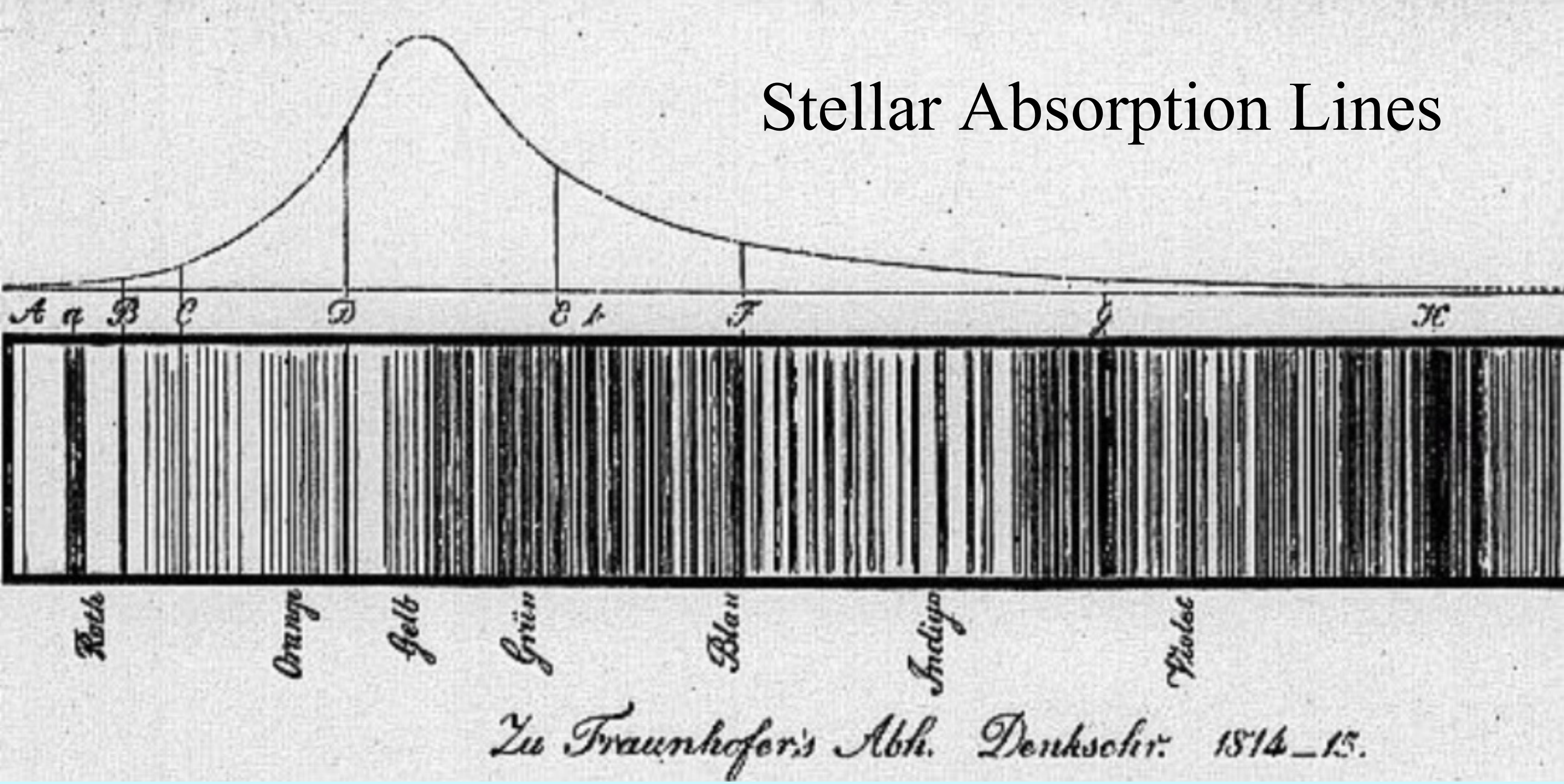




Hydrogen Lines

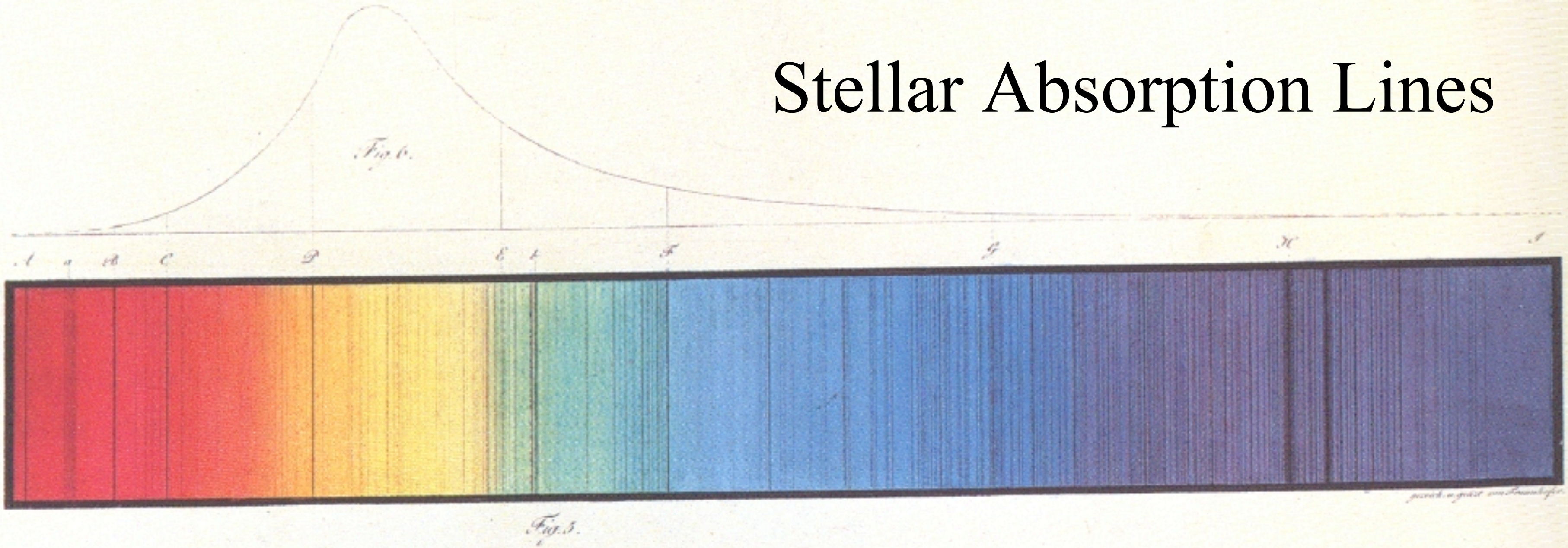


Stellar Absorption Lines



Joseph Ritter von Fraunhofer was the first person to perform extraterrestrial spectroscopy. (He observed the Sun.) Fraunhofer noticed many dark absorption lines, and labeled the darkest of these with letters A-K in order of wavelength (red to blue).

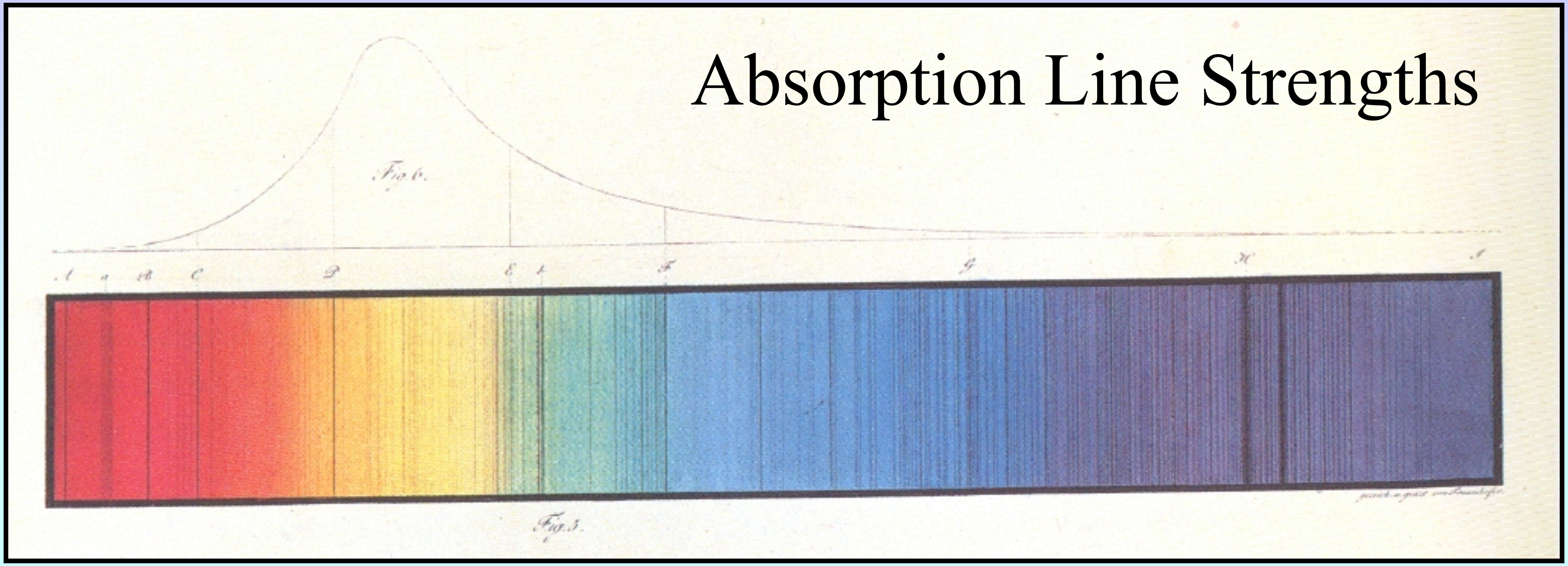
Stellar Absorption Lines

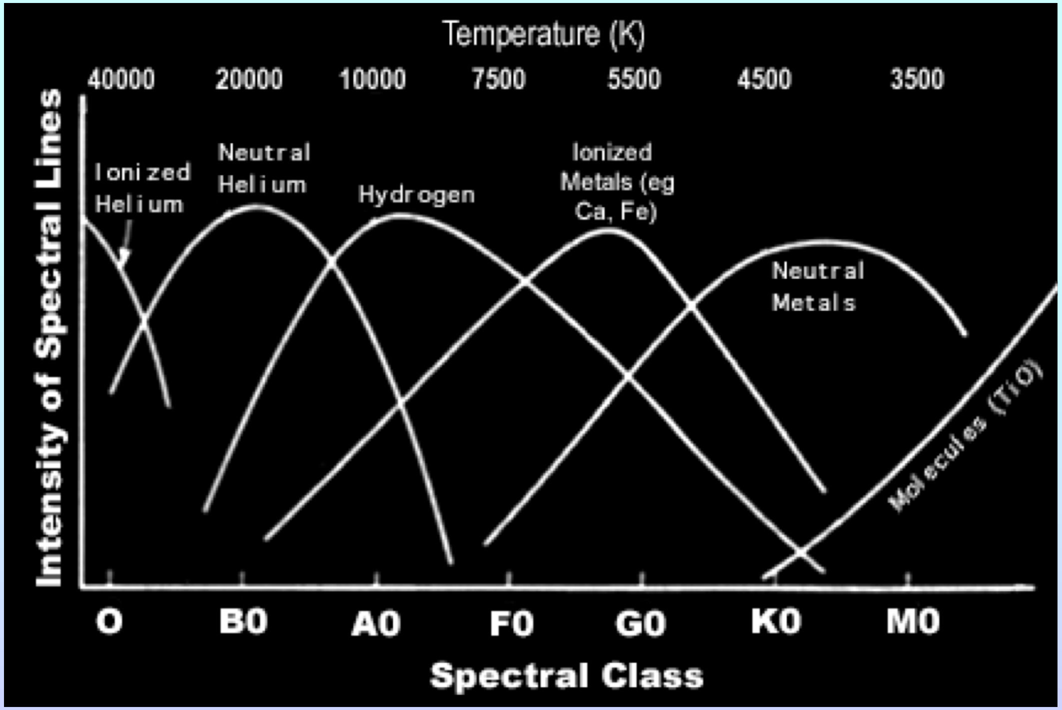


Some of Fraunhofer’s names are still with us today.

Designation	Wavelength (Å)	Origin
A-band	7600 - 7630	Telluric
B-band	6860 - 6890	Telluric
D-lines	5890, 5896	Sodium
G-band	4295 - 4315	CH complex
H	3968	Calcium
K	3934	Calcium

Absorption Line Strengths

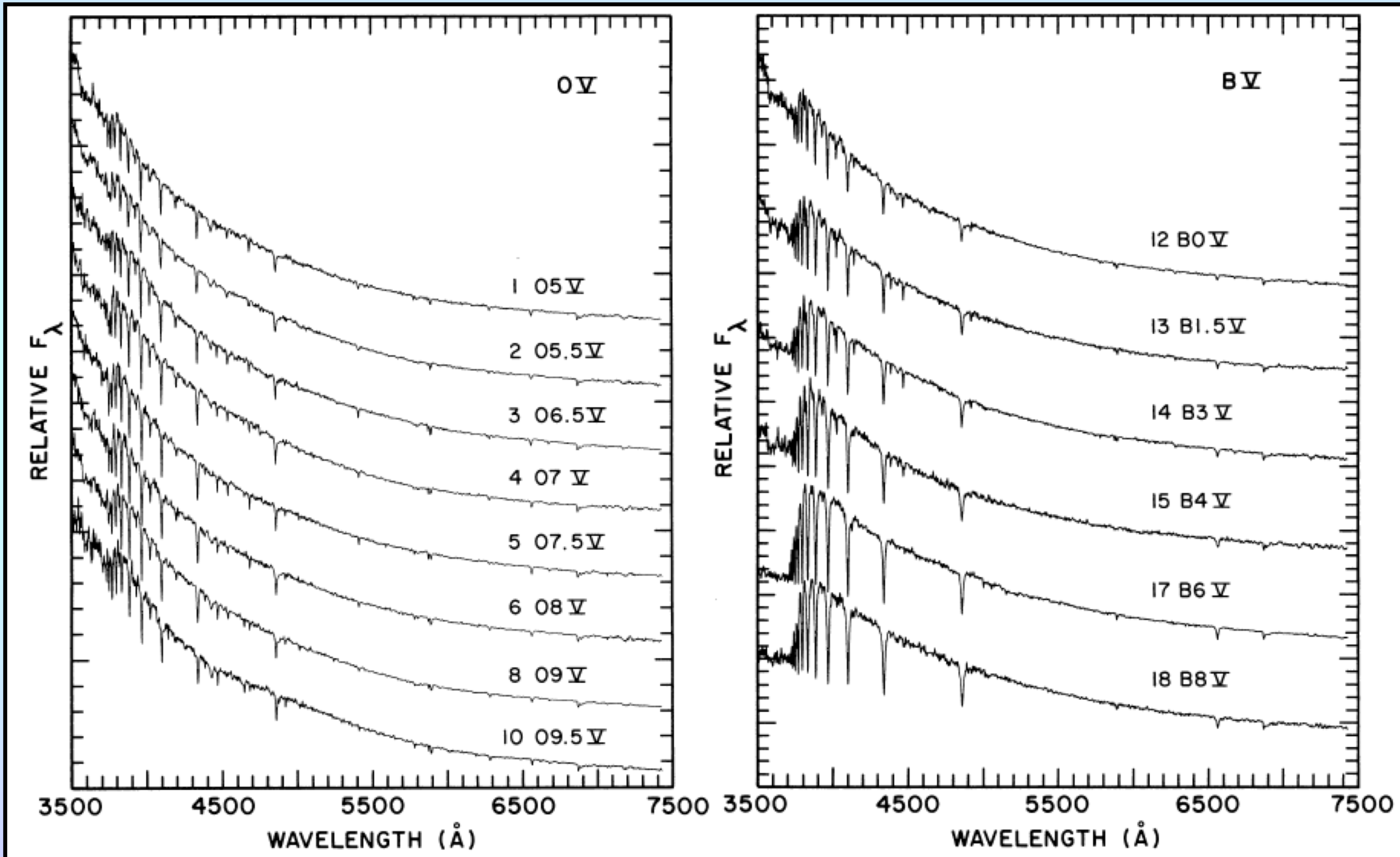




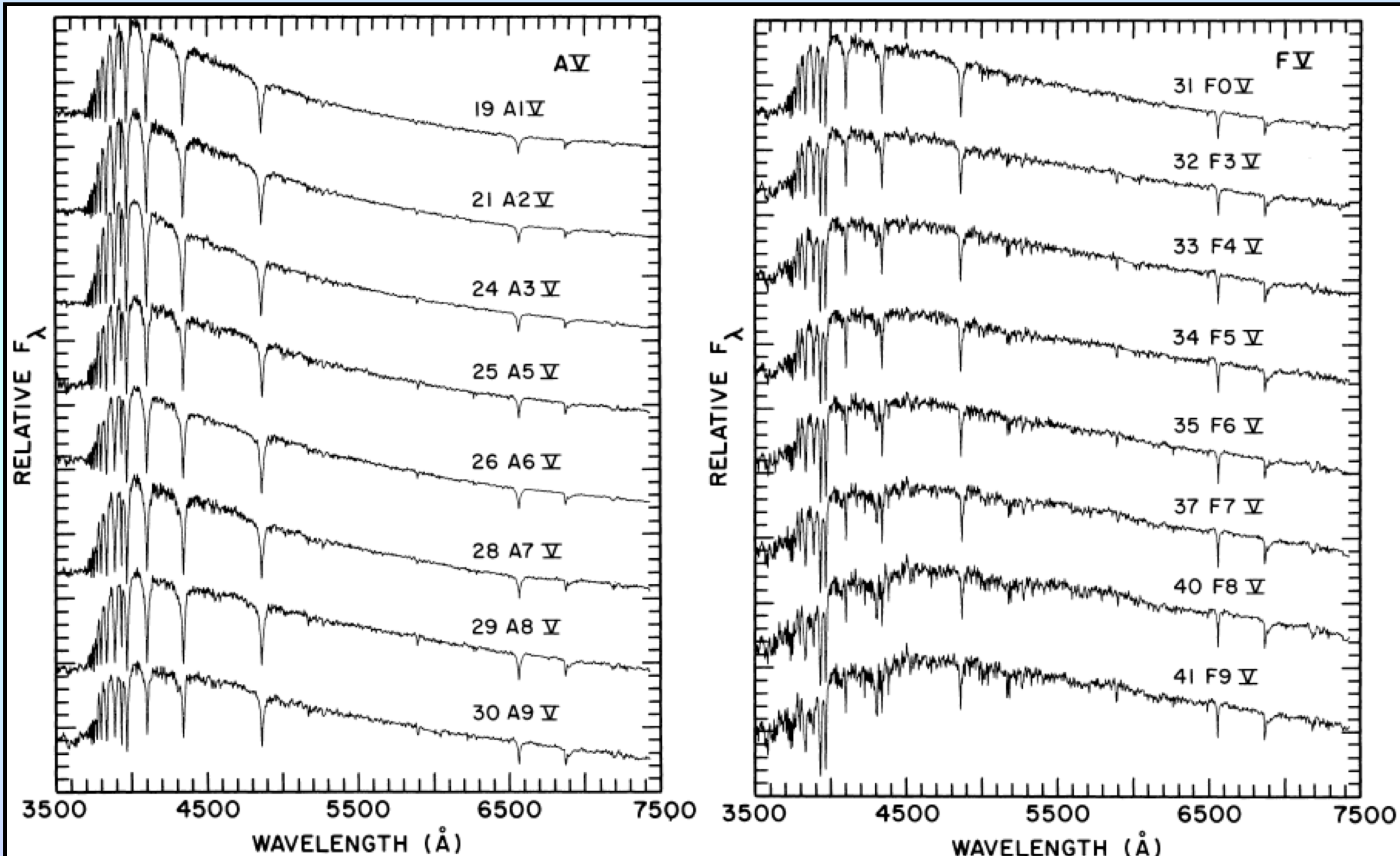
The strength of a given stellar absorption line is largely determined Saha equation and the Boltzmann distribution, along with the species' abundance.

Stellar Spectral Types: O and B Dwarfs

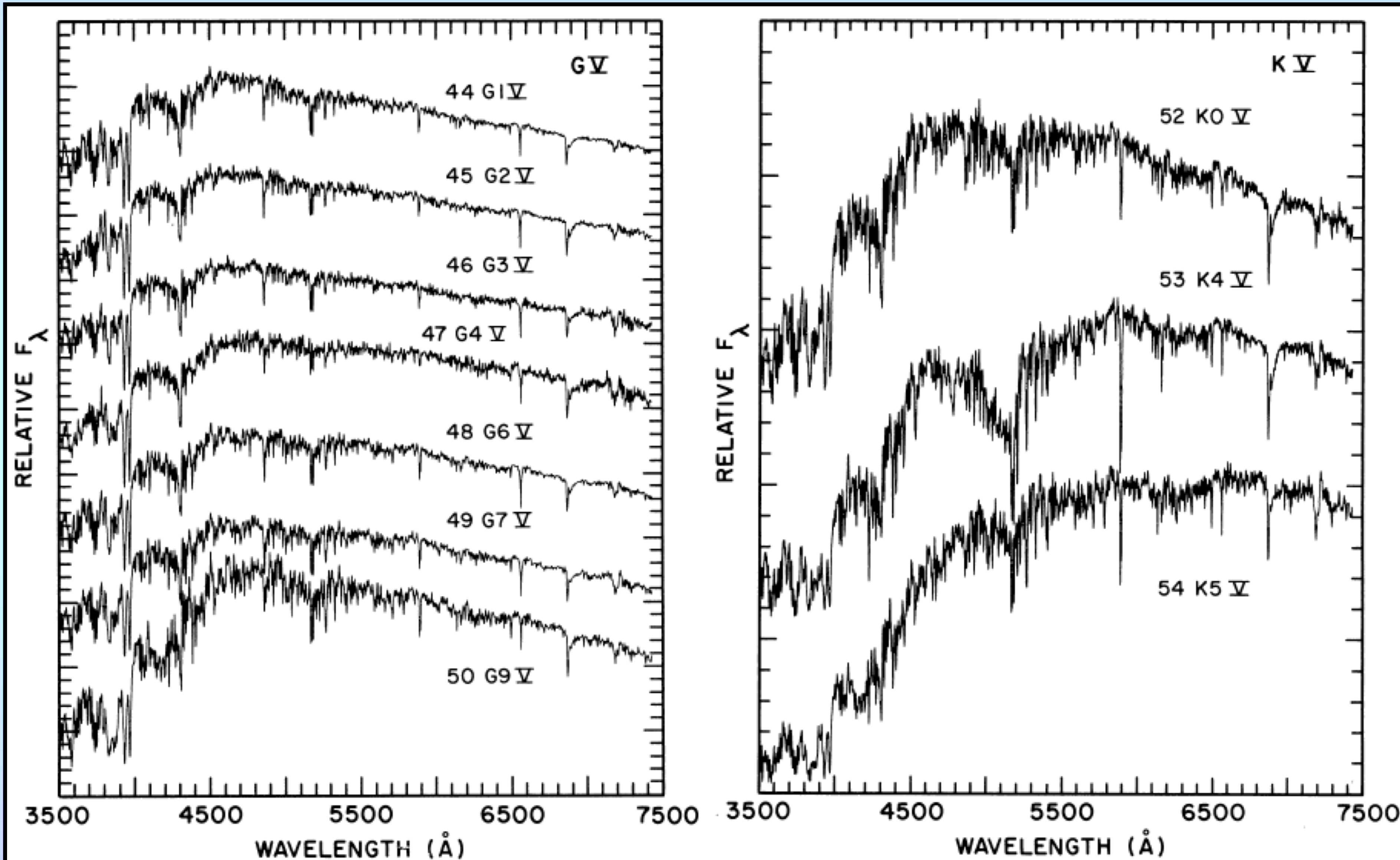
[Jacoby et al. 1984, ApJSupp, 56, 257]



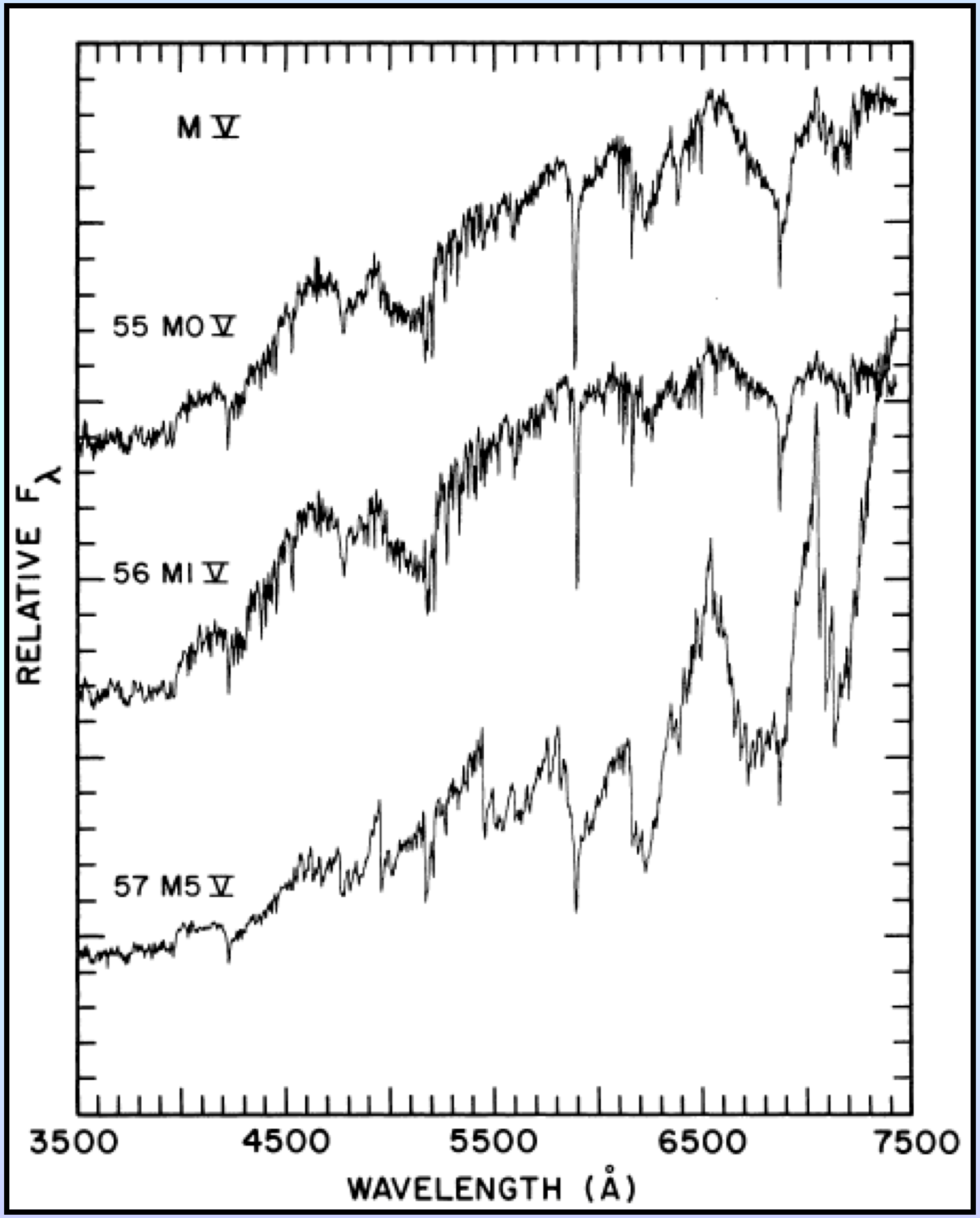
Stellar Spectral Types: A and F Dwarfs



Stellar Spectral Types: G and K Dwarfs

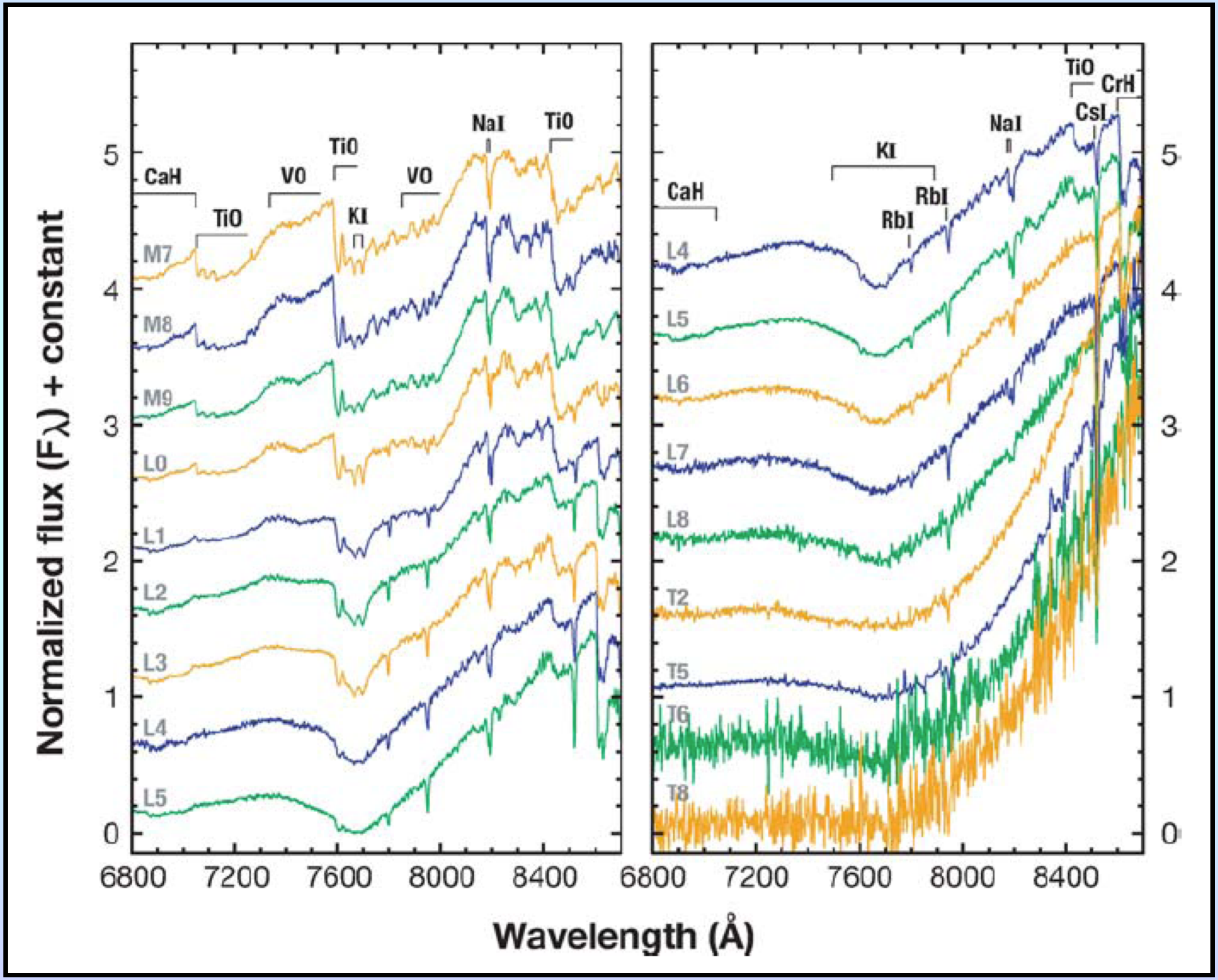


Stellar Spectral Types: M Dwarfs



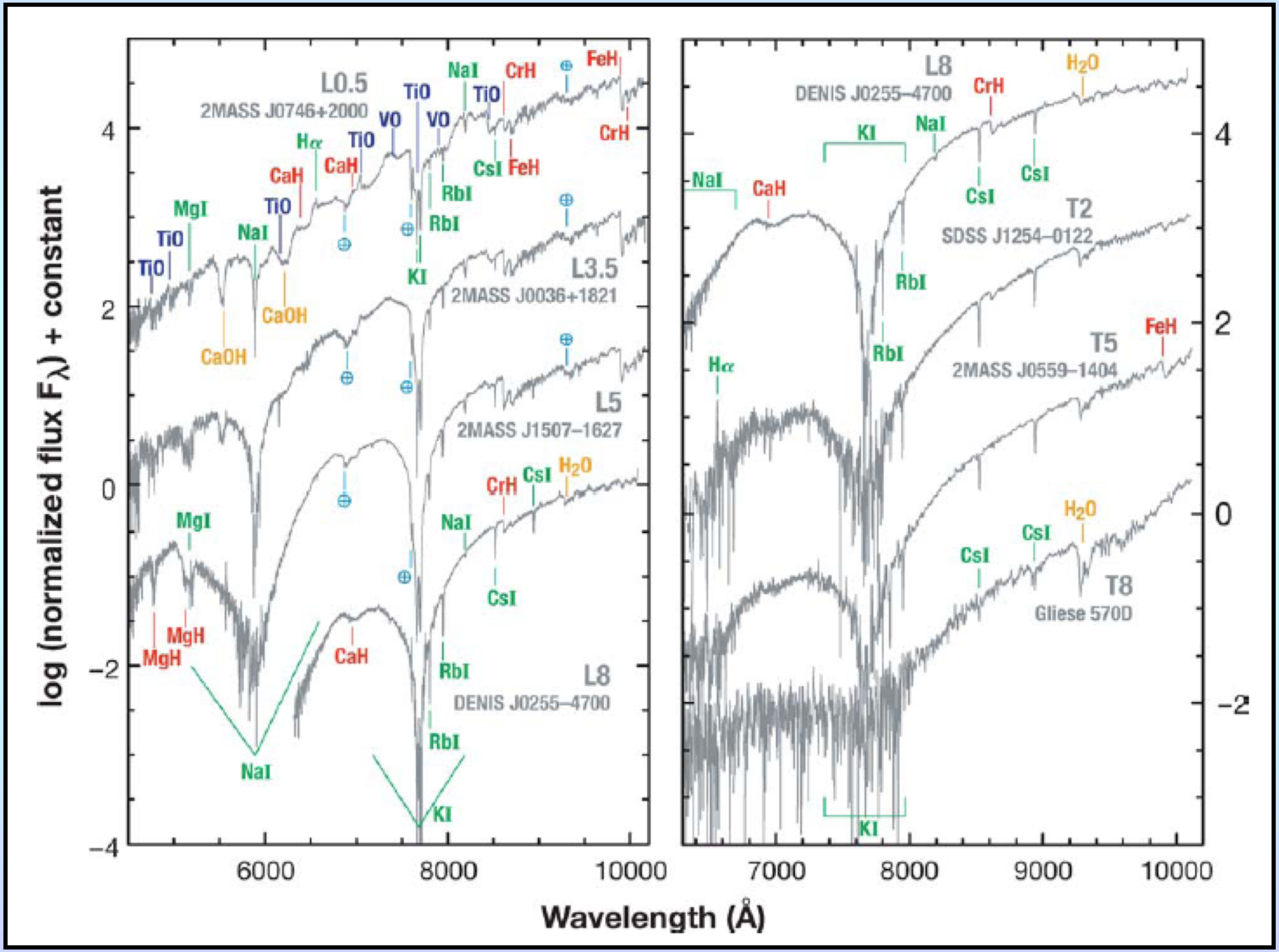
Stellar Spectral Types: L and T Dwarfs

[Kirtpatrick 2005, ARA&A, 43, 195]

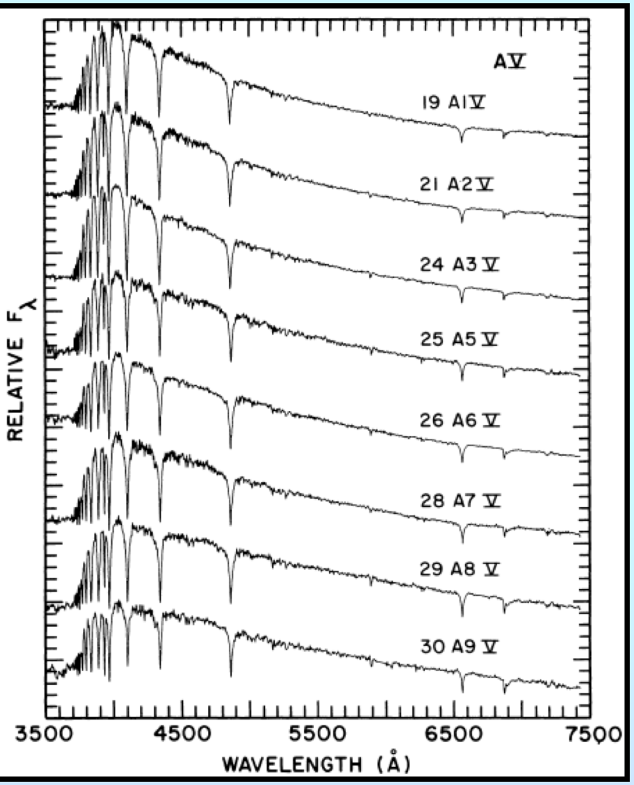


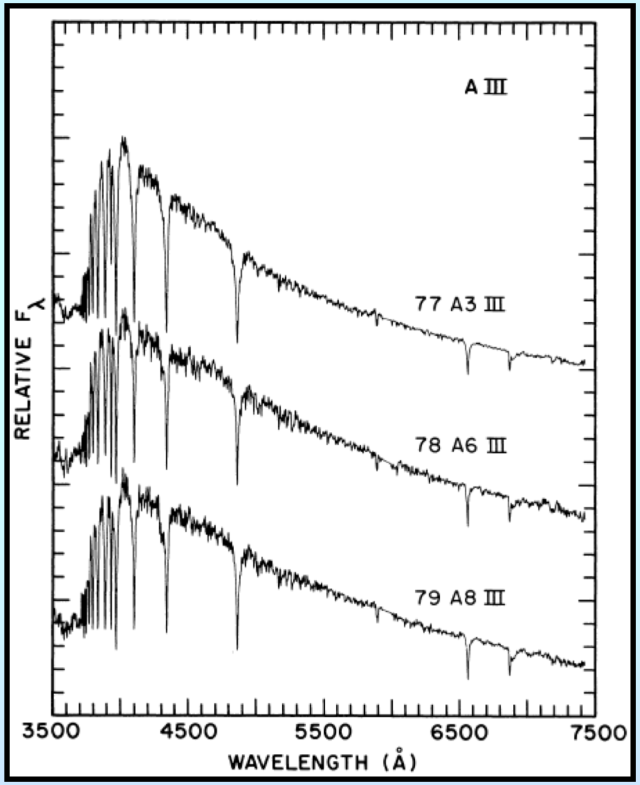
Stellar Spectral Types: L and T Dwarfs

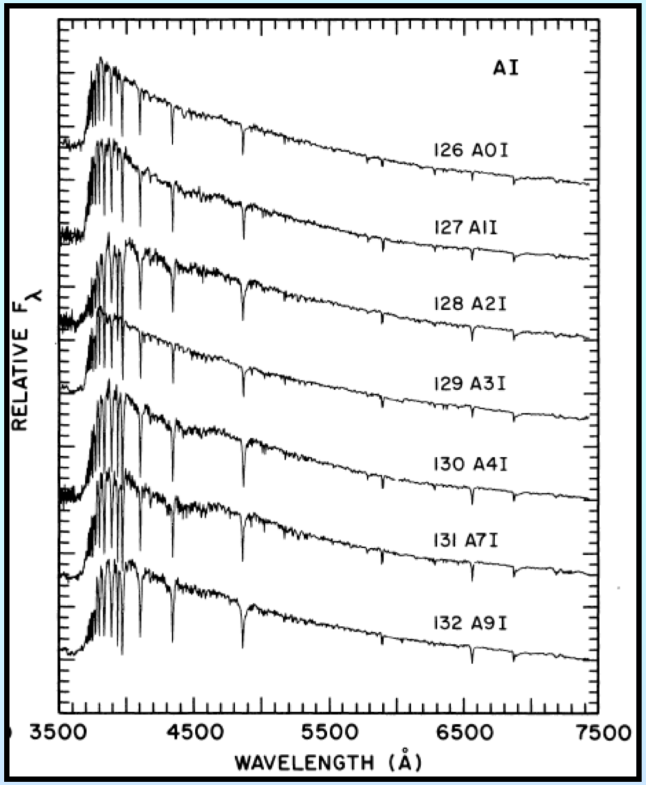
[Kirtpatrick 2005, ARA&A, 43, 195]



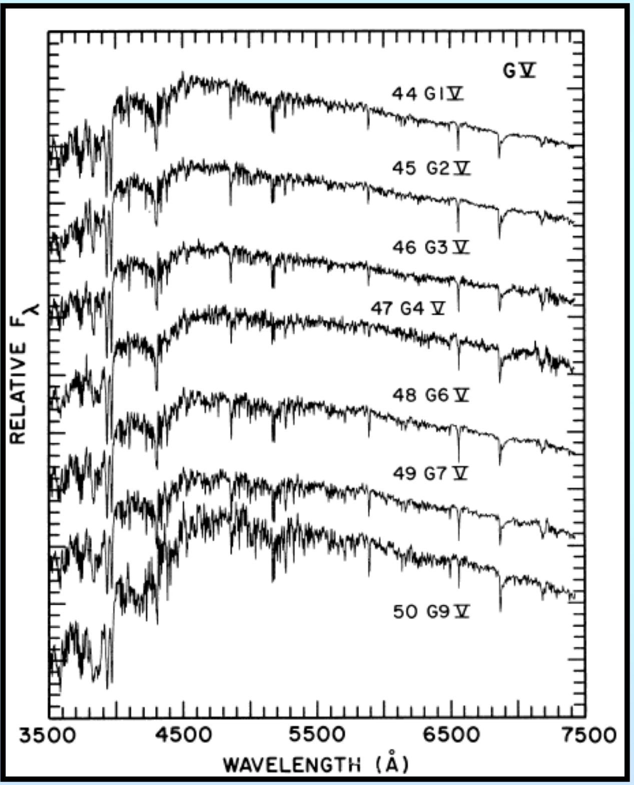
Stellar Spectral Types: A Dwarfs, Giants, and Supergiants

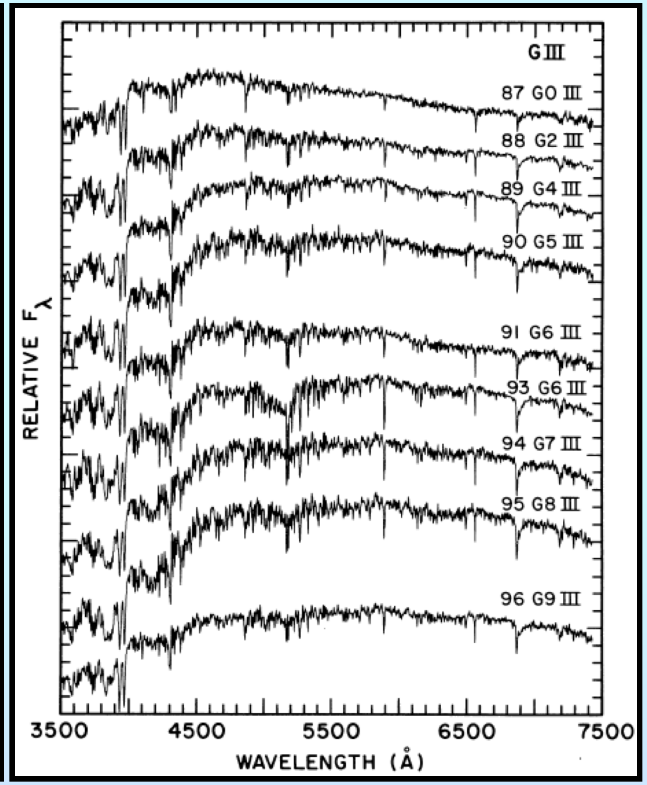


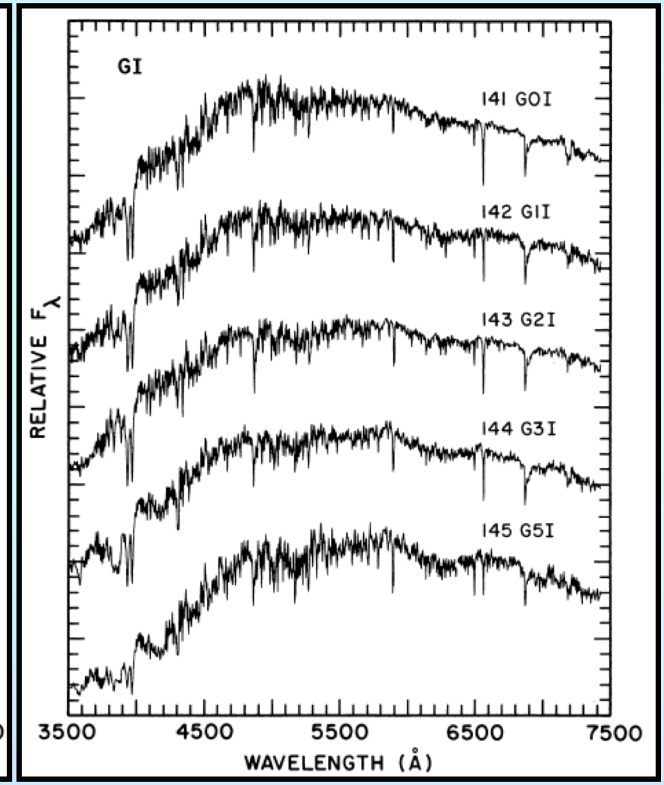




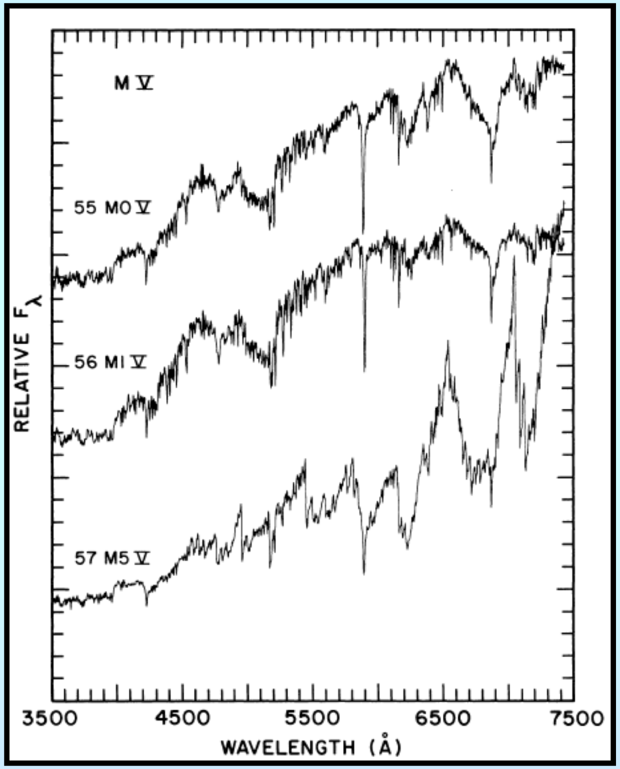
Stellar Spectral Types: G Dwarfs, Giants, and Supergiants

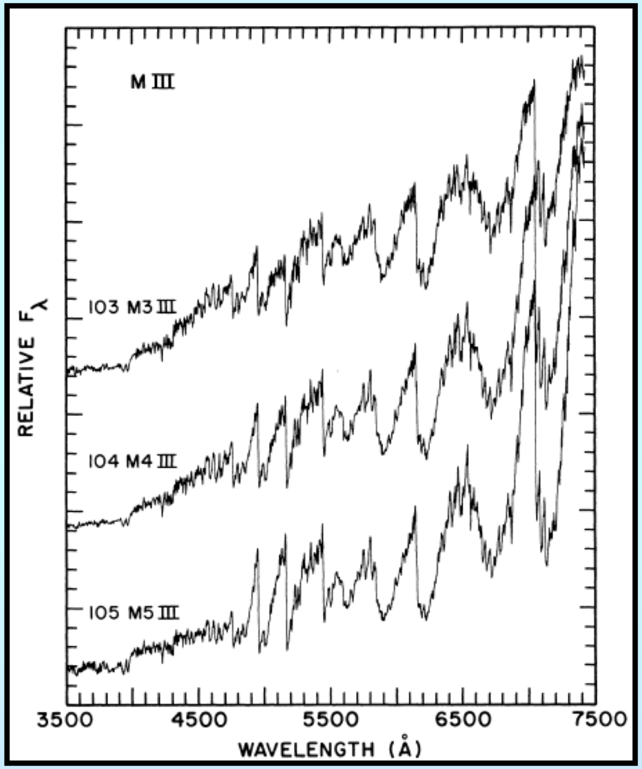


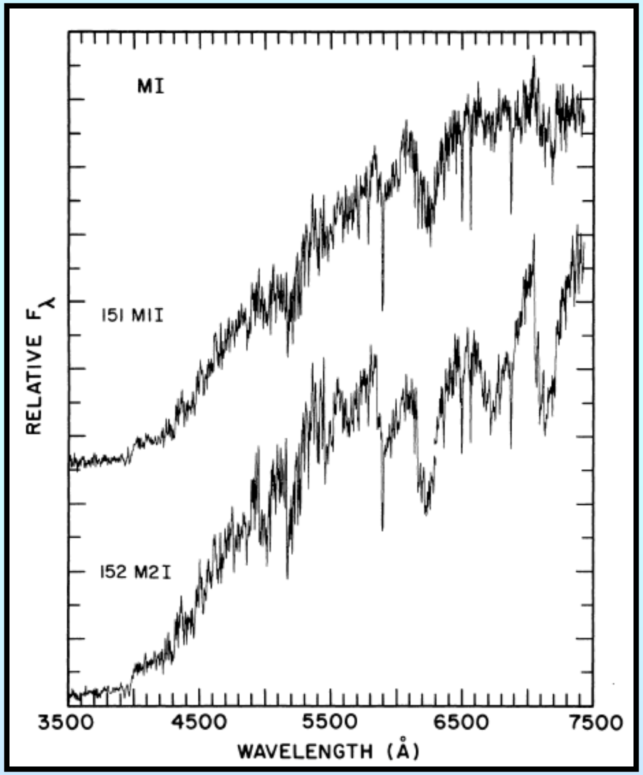




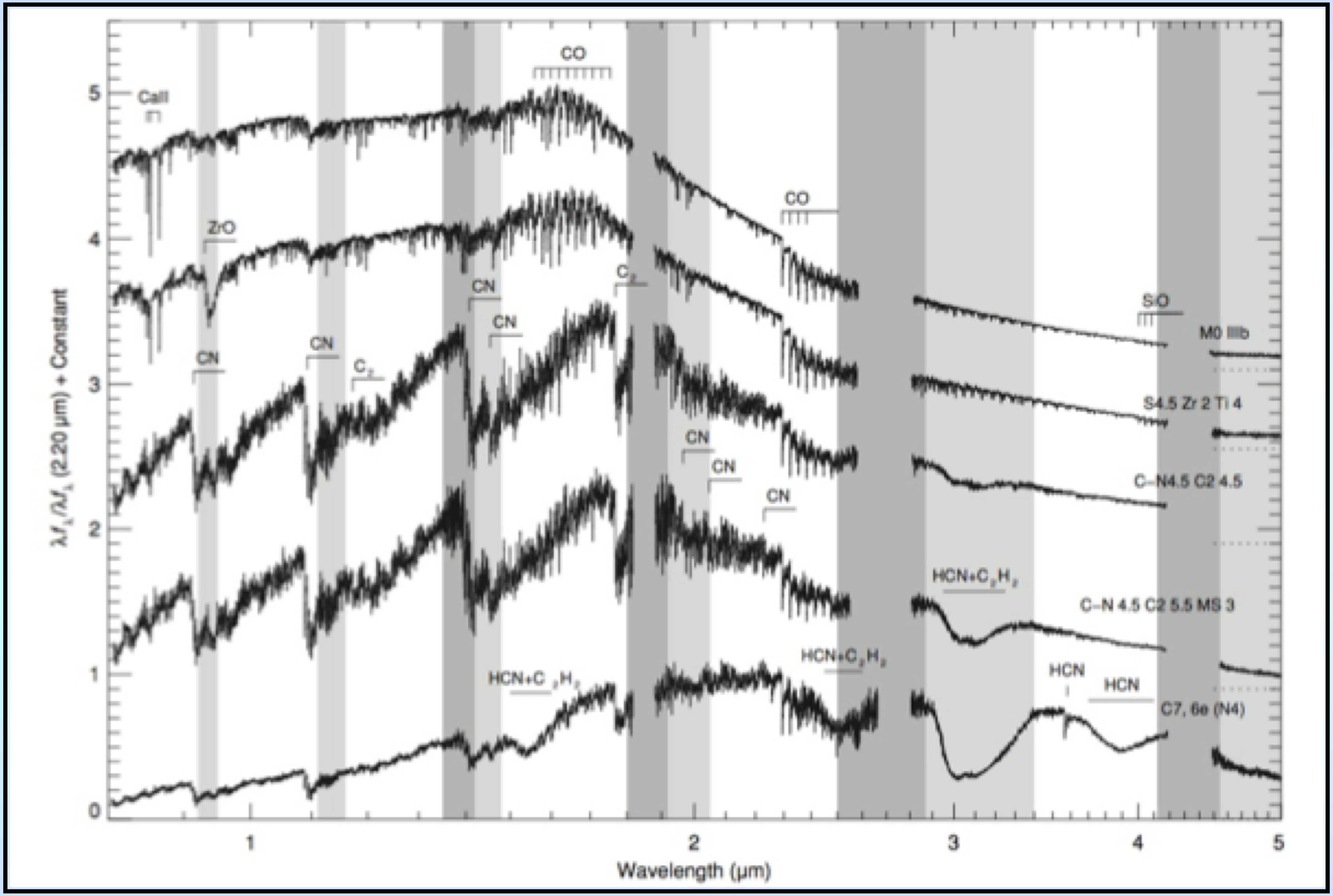
Stellar Spectral Types: M Dwarfs, Giants, and Supergiants





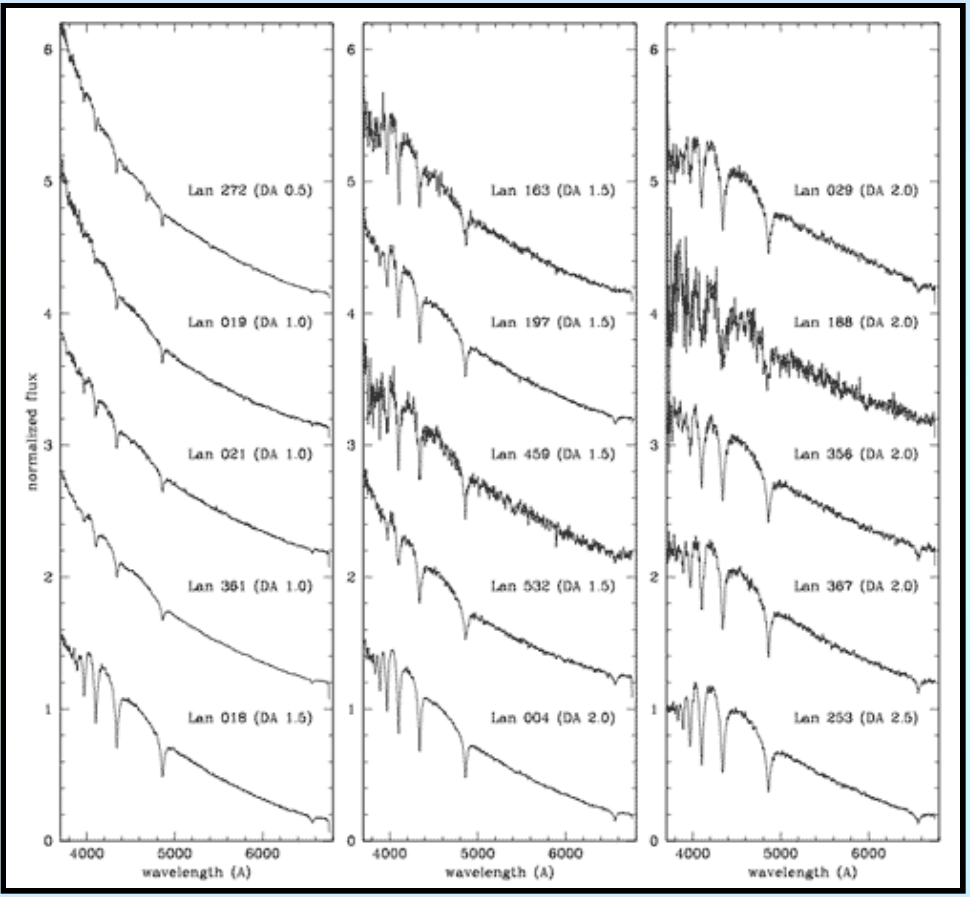


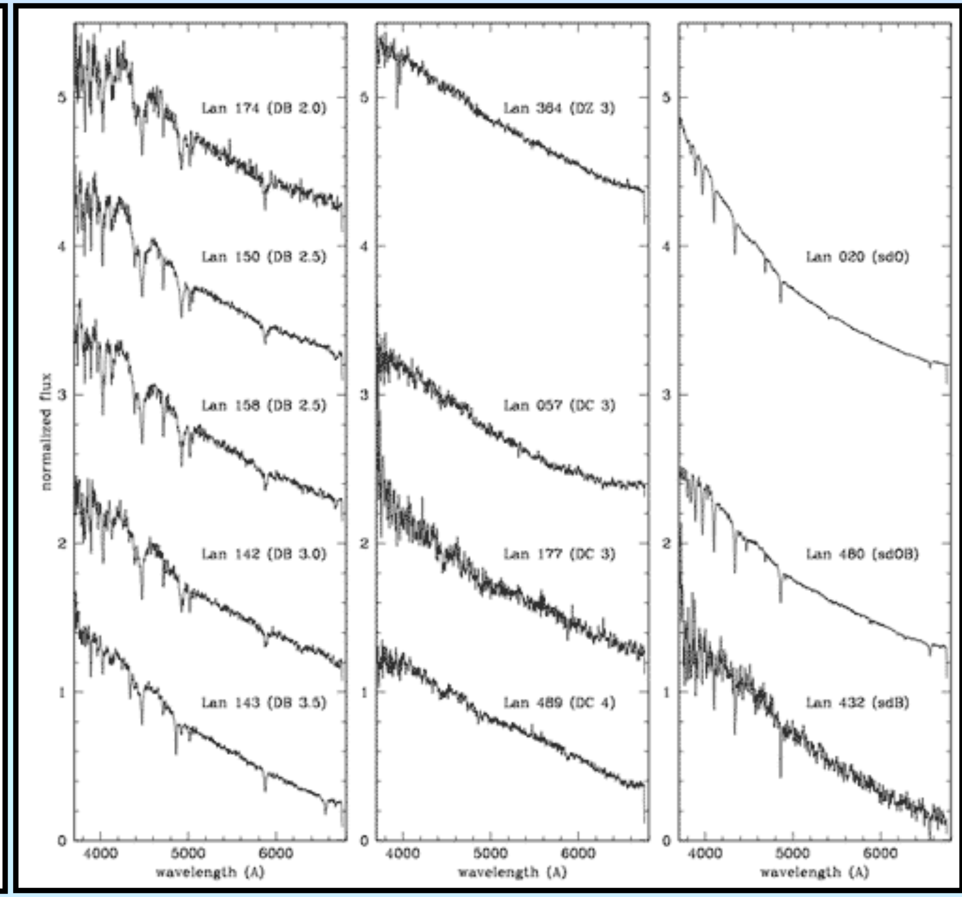
Stellar Spectral Types: M, S, and C Giants



Similar temperature, different C/O ratio

Stellar Spectral Types: DA, DB, and DC White Dwarfs





DA: Hydrogen absorption, but no helium or metals

DB: Helium absorption, but no hydrogen or metals

DC (or DZ): metal absorption, but no hydrogen or helium

Stellar Spectral Type and Temperature

Dwarfs

Spectral Type	Temperature
O5	40,000
B0	28,000
B5	15,500
A0	9,900
A5	8,500
F0	7,400
F5	6,880
G0	6,030
G5	5,520
K0	4,900
K5	4,130
M0	3,480
M5	2,800
M8	2,400

Giants

Spectral Type	Temperature
G0	5,600
G5	5,000
K0	4,500
K5	3,800
M0	3,200

Supergiants

Spectral Type	Temperature
B0	30,000
A0	12,000
F0	7,000
G0	5,700
G5	4,850
K0	4,100
K5	3,500

Photometric Systems

[Bessell 2005, ARA&A, 43, 293]

[Landolt 2007, ASP Conf. Ser. 364, 27]

There are several commonly used filter systems in astronomy. Their pass bands are defined by

a) the transmission of colored glass (or gel)

b) the efficiency of the telescope optics and detector

c) the transmittance of the atmosphere

The photometric systems themselves are defined by measurements of "standard stars". Since no two pieces of glass (or detectors or atmospheric locations) are identical, standard star observations are critical to the calibration.

Magnitude Systems

The brightnesses (and colors) of stars are expressed in a logarithmic system called magnitudes

$$m = -2.5\log\frac{\int S(\nu)F(\nu)d\nu}{\int S(\nu)d\nu} + C$$

where $S(\nu)$ is the sensitivity of the filter plus detector plus atmosphere, $F(\nu)$ is the flux density of the object in flux/Hz (as in ergs/s/cm^2/Hz), and C is a constant of the filter system.

Note that the units of magnitudes are flux-density, i.e., they represent the filter-weighted "average" amount of flux coming through the bandpass. Usually, this is given as ergs/cm^2/s/Hz or Janskies, where 1 Jy = 10^{-26} W/m^2/Hz = 10^{-23} ergs/s/cm^2/Hz.

Since the denominator of the equation is entirely a function of the filter, as is C, the two terms are usually combined, so one usually sees

$$m = -2.5\log\int S(\nu)F(\nu)\,d\nu + C$$

Filter Central Wavelengths

The central wavelength of any filter is traditionally defined through

$$\left\langle \frac{c}{\lambda_{\text{eff}}} \right\rangle = \frac{\int \nu\, S(\nu) F(\nu)\, d\nu}{\int S(\nu) F(\nu)\, d\nu}$$

Although often it will be defined using

$$\lambda_{\text{eff}} = \frac{\int \lambda\, S(\lambda) F(\lambda)\, d\lambda}{\int S(\lambda) F(\lambda)\, d\lambda}$$

(They're not quite the same!) Either way, the central wavelength is a function of the input spectrum; the broader the filter, the greater the dependence on $F(\lambda)$, which is generally unknown!

Magnitude Zero Points

The absolute flux entering a telescope is extremely difficult to measure. However, it is relatively simple to measure the *relative* brightness of one star to another. Therefore one always measures magnitudes relative to stars with previously assigned magnitudes. The most common zero points are

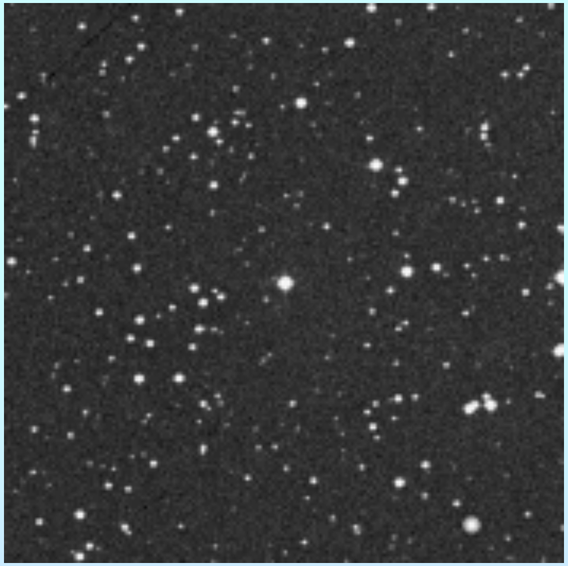
- Vega-based magnitudes: the star α Lyr is assigned $m = 0$
- AB-magnitudes: $m = 0$ is assigned 3.63×10^{-20} ergs/cm^2/s/Hz (*i.e.*, $m = -2.5 \log F_\nu - 48.60$), regardless of wavelength
- ST-magnitudes: $m = 0$ is assigned 3.63×10^{-9} ergs/cm^2/s/Å (*i.e.*, $m = -2.5 \log F_\lambda - 21.10$), regardless of wavelength

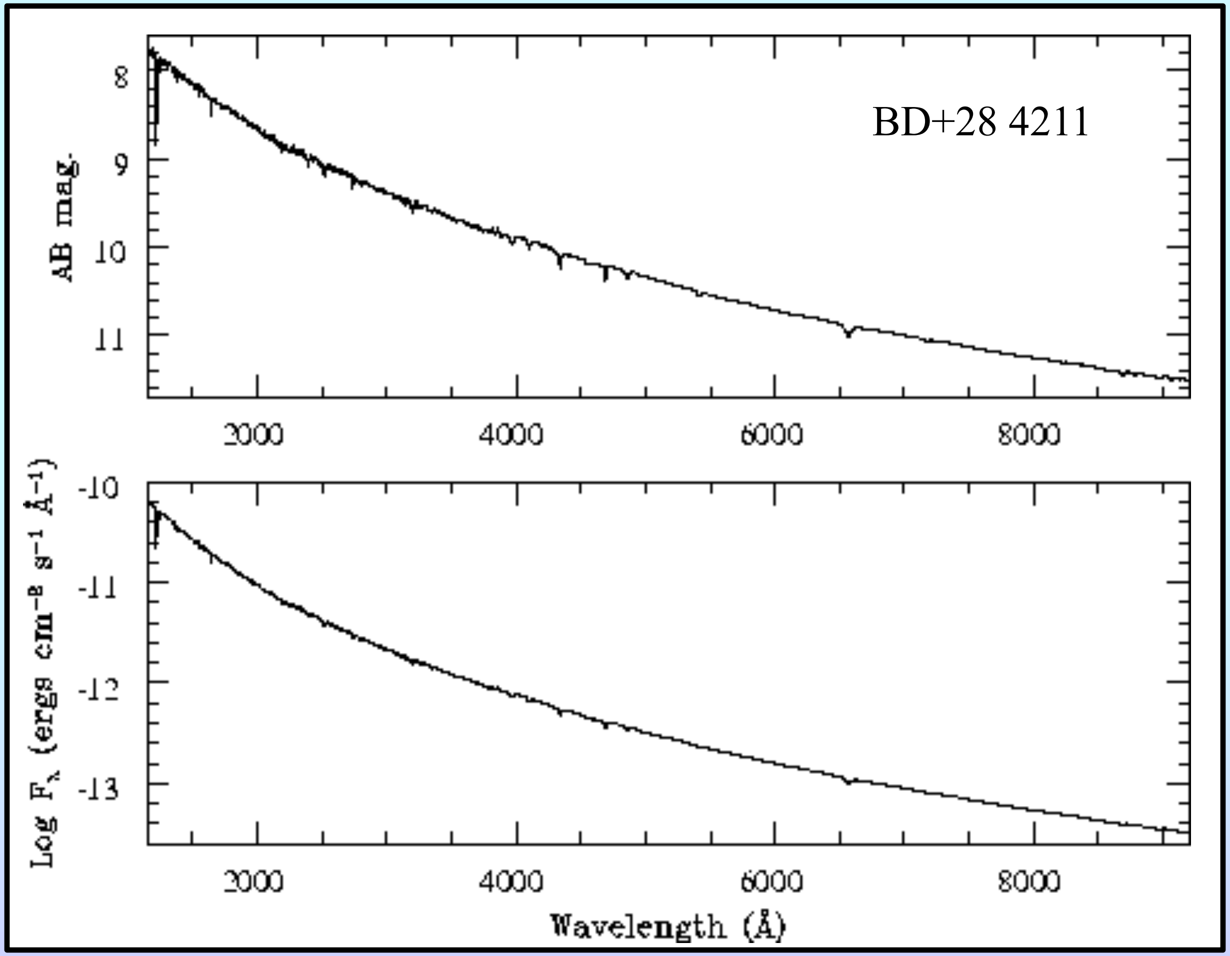
In all cases, the task of figuring out brightnesses of the fundamental standards is left to someone else.

Note: In the visual, the photon flux from a V = 0 star is very close to 1000 photons/cm^2/sec/Å

Standard Stars

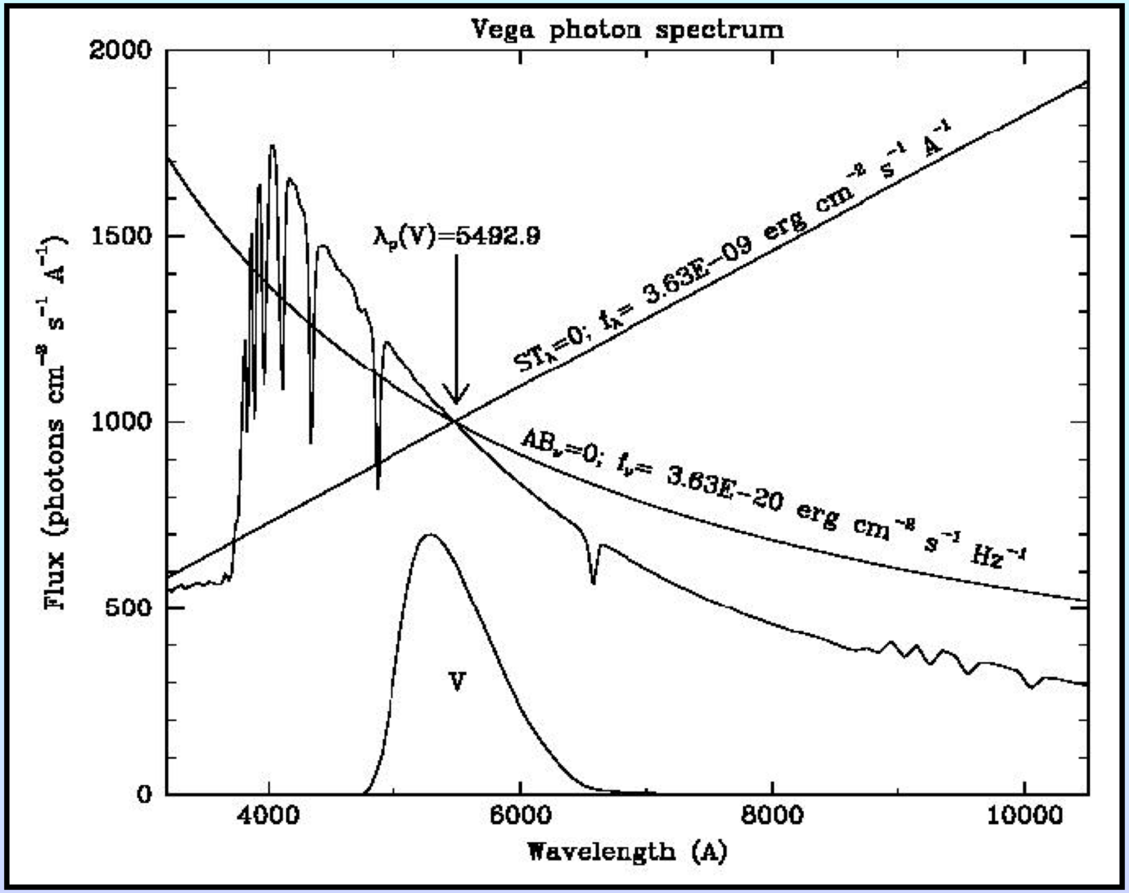
Most telescopes cannot observe targets are bright as Vega. So in practice, secondary standard stars define the various magnitude systems. Some of these are defined photometrically, some through spectrophotometry.





Vega-Based Magnitude Zero Points

The traditional UBVRIJHK photometry uses Vega as its ultimate zero point. More and more, however, the AB system is being used, even for these Johnson filters. Make sure you know what system you're in!



Filter	λeff	m=0 (ergs/cm²/s/Hz)
U	3650 Å	1.72×10^{-20}
B	4400 Å	4.49×10^{-20}
V	5500 Å	3.66×10^{-20}
R	7000 Å	2.78×10^{-20}
I	9000 Å	2.24×10^{-20}
J	1.25 μm	1.58×10^{-20}
H	1.65 μm	1.04×10^{-20}
K	2.20 μm	6.32×10^{-21}
L	3.40 μm	2.74×10^{-21}
M	5.00 μm	1.56×10^{-21}
N	10.2 μm	3.84×10^{-22}

The UBV + (RI) System

[Johnson and Morgan 1953, ApJ 117, 313]
[Cousins 1974, MNRAS, 166, 711]
[Cousins 1974, MNASSA, 33, 149]
[Bessell 1979, PASP, 91, 589]
[Bessell 1990, PASP, 102, 1181]

This is the oldest system, which is largely defined by

a) the atmospheric UV cutoff (for U)

b) the sensitivity of old photographic plates (for B)

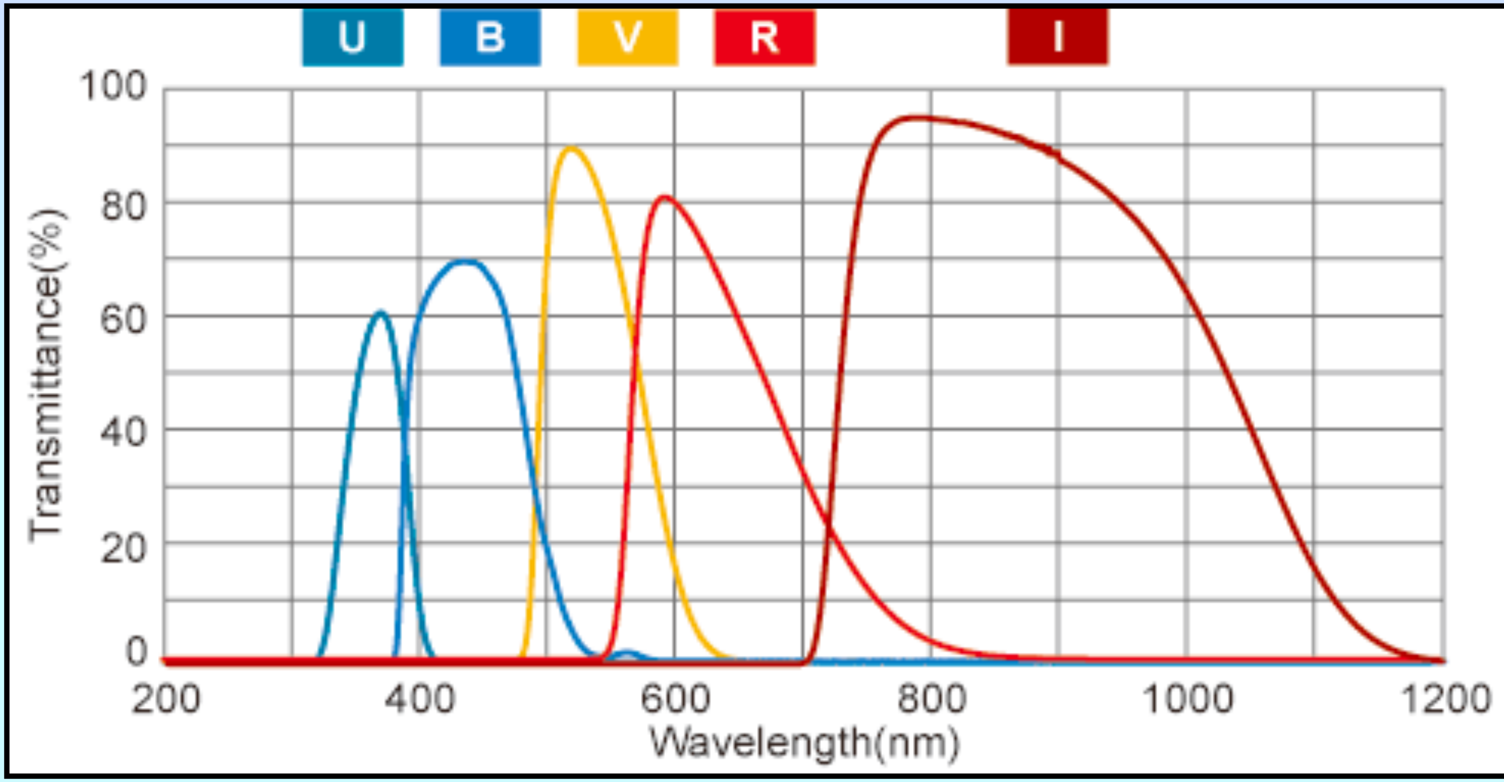
c) the sensitivity of the human eye and the 1P21 PMT (for V)

d) the red sensitivity of the S20 PMT (for R)

Advantage: Historical system, so lots of data available
Wide bandpasses, so useful for faint objects

Disadvantage: Historical system, so not astrophysically driven
Broad bandpasses, so central wavelengths ill-defined

The UBV + (RI) System



Filter	λ_{eff}	FWHM
U	3600 Å	660 Å
B	4400 Å	980 Å
V	5500 Å	870 Å
R	7000 Å	2070 Å
I	9000 Å	2310 Å

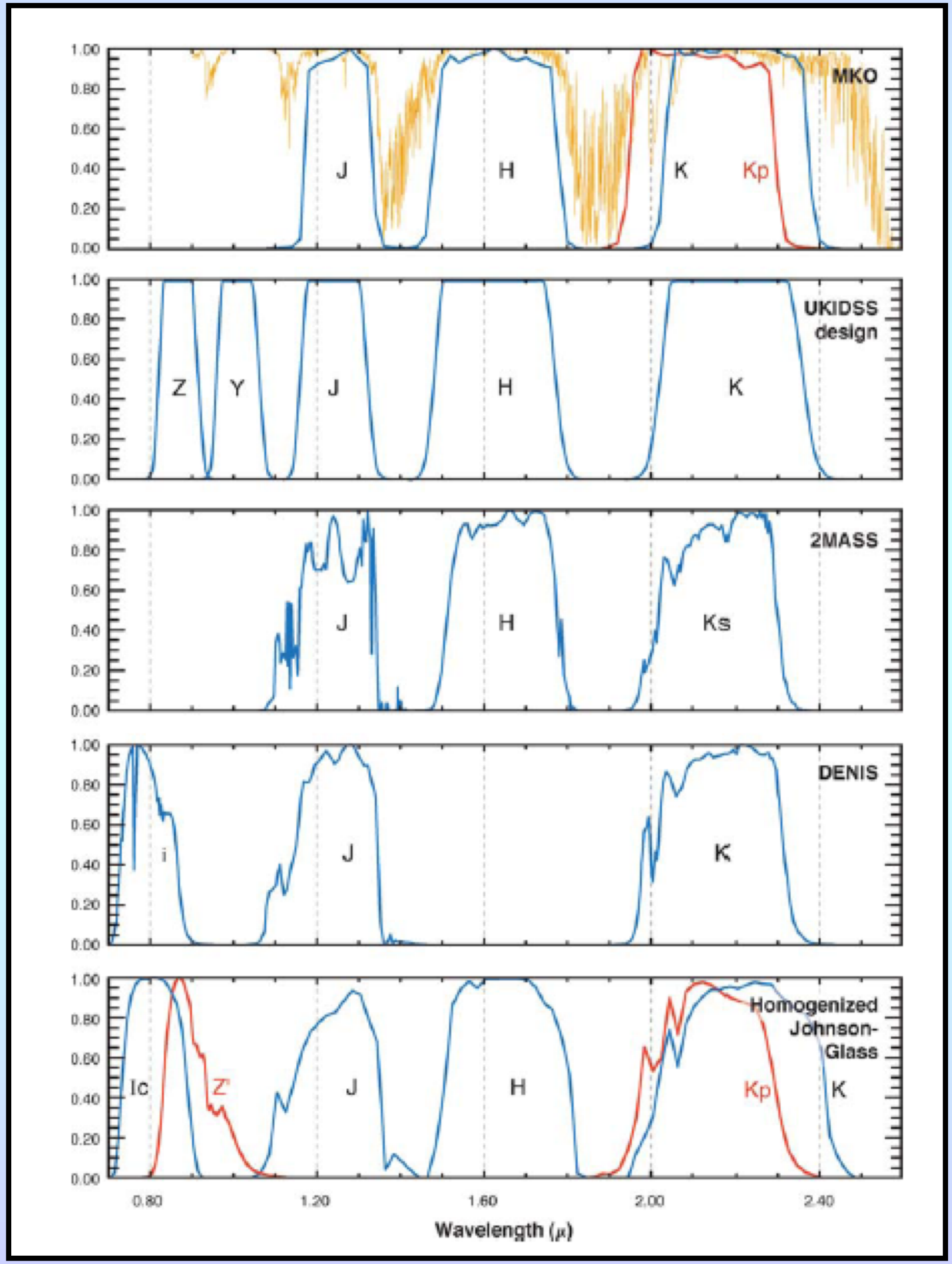
Note: not all R and I filters are identical; care must be taken not to mix up Johnson-R magnitudes with Cousins-R magnitudes with Harris-R magnitudes, etc.

Infrared Extension to Johnson (JHK and LM)

[Johnson 1966, ARA&A, 4, 193]
[Bessell 2005, ARA&A, 43, 293]

Infrared photometric systems are less standardized than optical systems. Each observatory has its own (slightly different) filters, and atmospheric transmission in the IR is highly dependent on water vapor.

Filter	λ_{eff}	FWHM
J	1.25 μm	0.16 μm
H	1.635 μm	0.29 μm
K	2.2 μm	0.34 μm
K'	2.12 μm	0.34 μm
K_s	2.15 μm	0.32 μm



Strömgren (*uvby*) System

[Strömgren 1963, QJRAS, 4, 8]

[Crawford 1975, AJ, 80, 955]

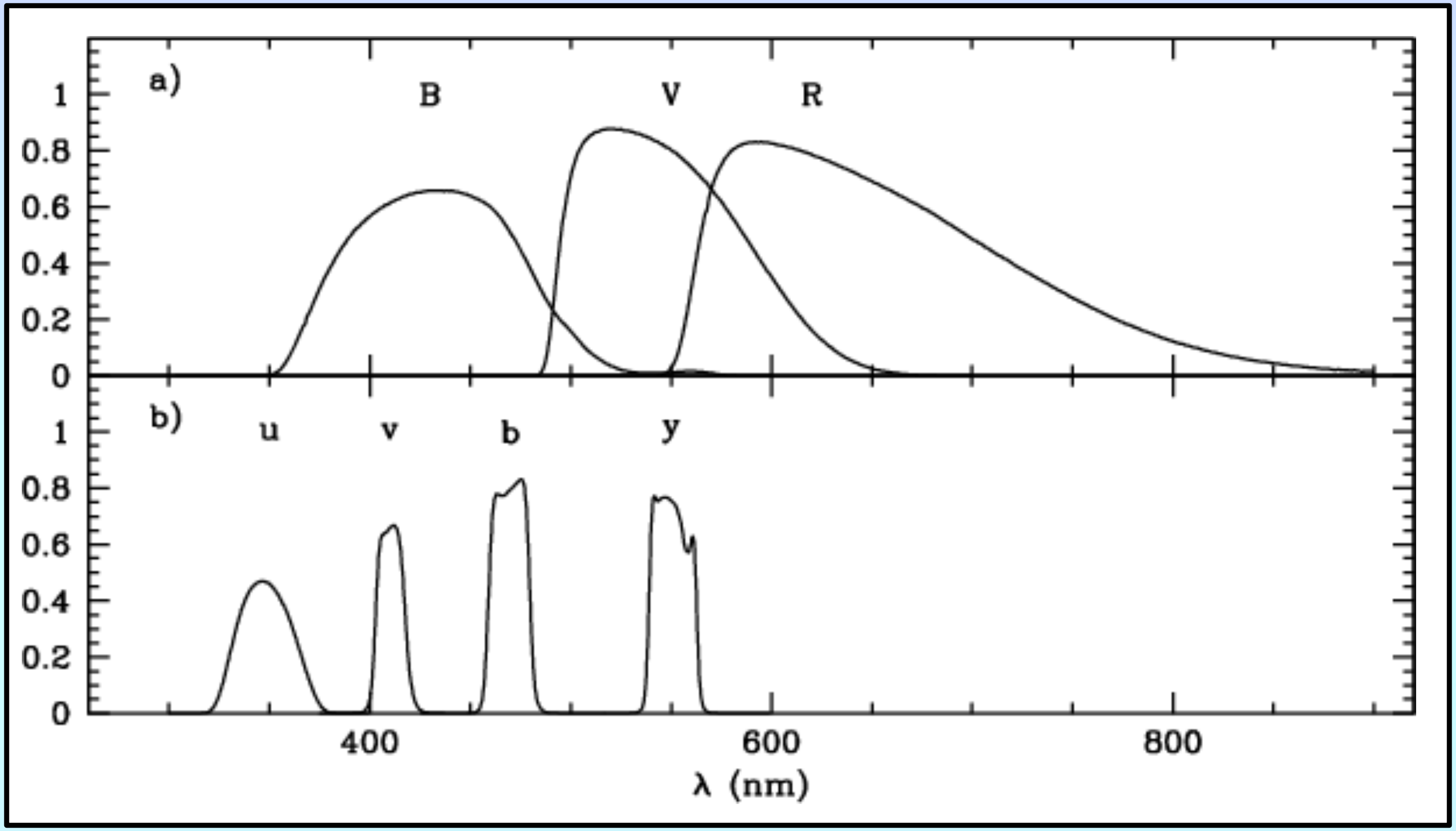
[Crawford & Barnes 1970, AJ, 978]

This is an intermediate-bandpass system, optimized for temperature, gravity, and metallicity measurements of intermediate-temperature (B, A, and F-type) stars.

Advantage: Defined with astrophysics (of warm stars) in mind

Disadvantage: Intermediate bandpasses, so restricted to brighter objects. Not particularly useful for late-type stars and galaxies

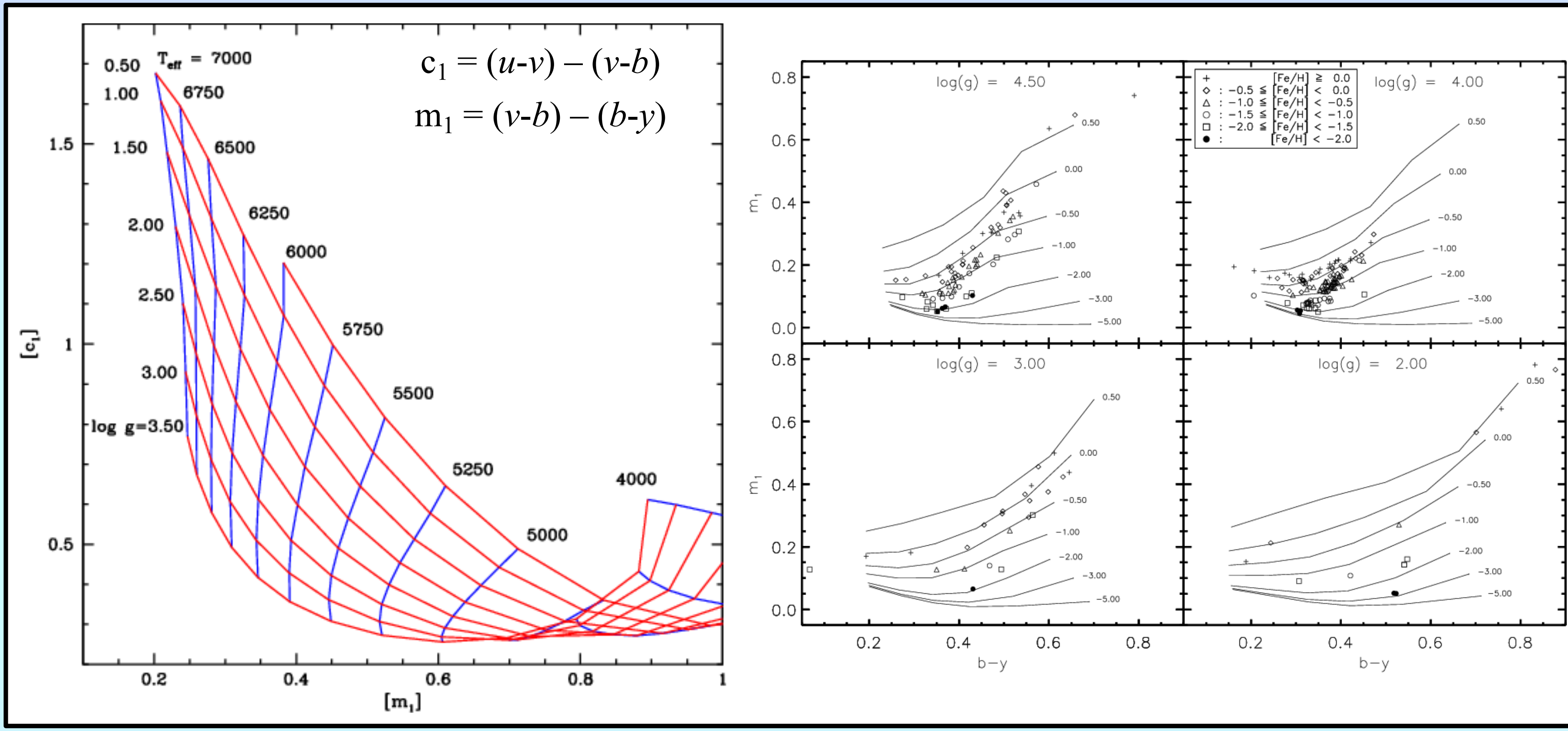
Strömgren (*uvby*) System



Filter	λ_{eff}	FWHM
u	3500 Å	340 Å
v	4100 Å	190 Å
b	4670 Å	180 Å
y	5470 Å	230 Å

The Strömgren filters are often supplemented with photometry through a narrow-band Hβ filter.

Strömgren (*uvby*) System



Strömgren indices work best for F-type stars; one can measure subtle differences in surface gravity (which are related to size, and therefore luminosity) and metallicity.

DDO Photometric System

[McClure & van den Bergh 1968, AJ 73, 313]

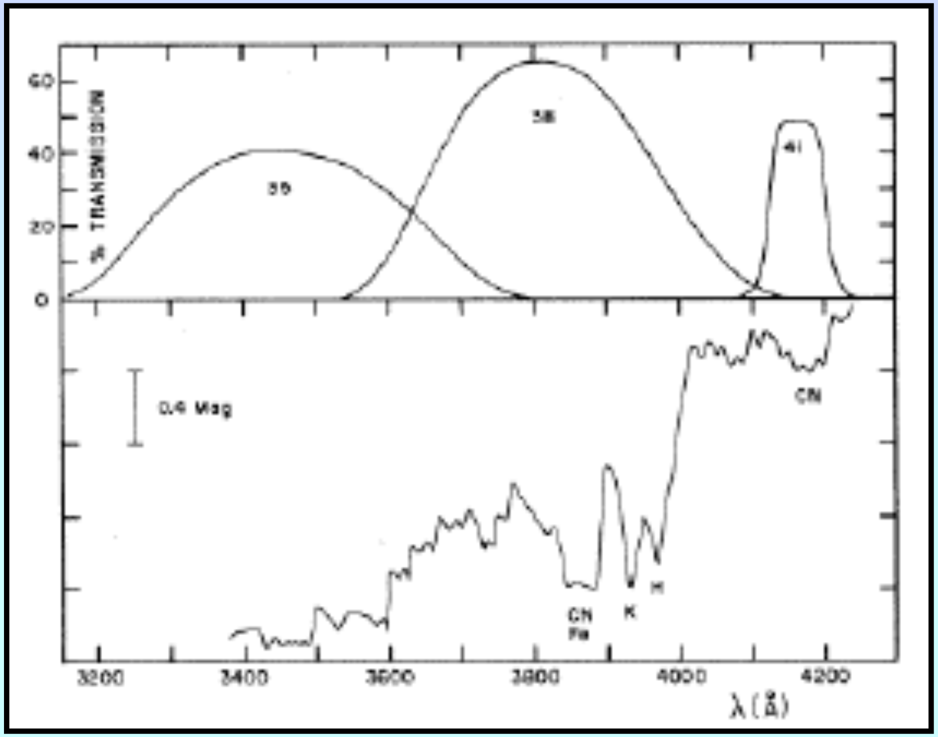
[Cousins & Caldwell 1996, MNRAS, 281, 522]

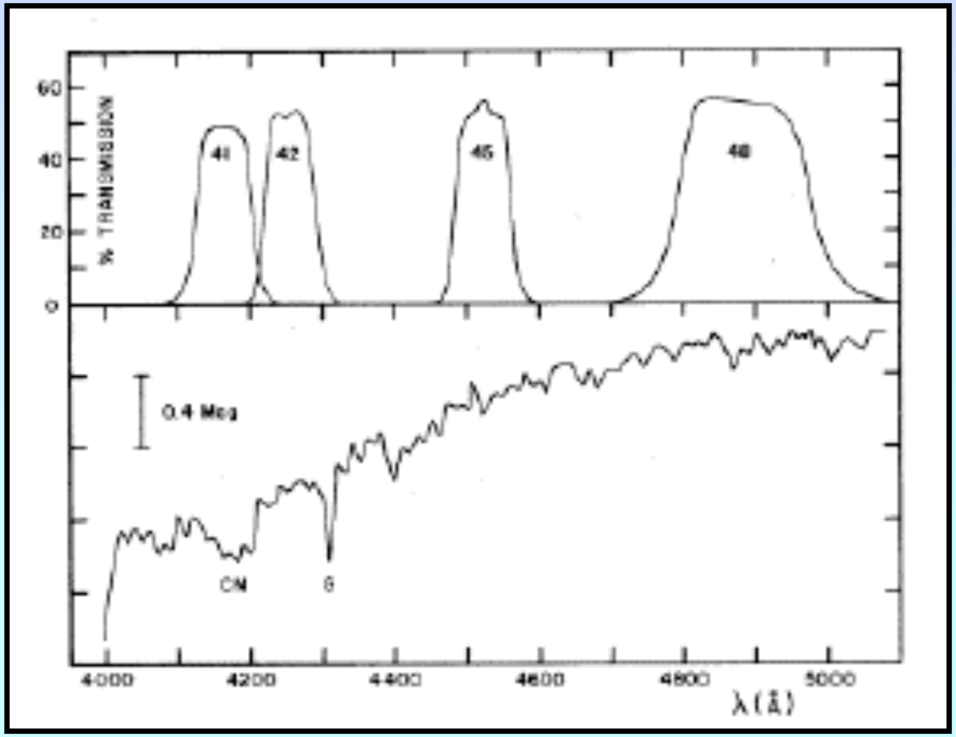
The **D**avid **D**unlop **O**bservatory system is an intermediate-bandpass set of filters, optimized for temperature and metallicity measurements of late-type (G and K) giants and dwarfs.

Advantage: Defined with astrophysics (of cool stars) in mind

Disadvantage: Intermediate bandpasses, so restricted to brighter objects. Not particularly useful for other projects

DDO System

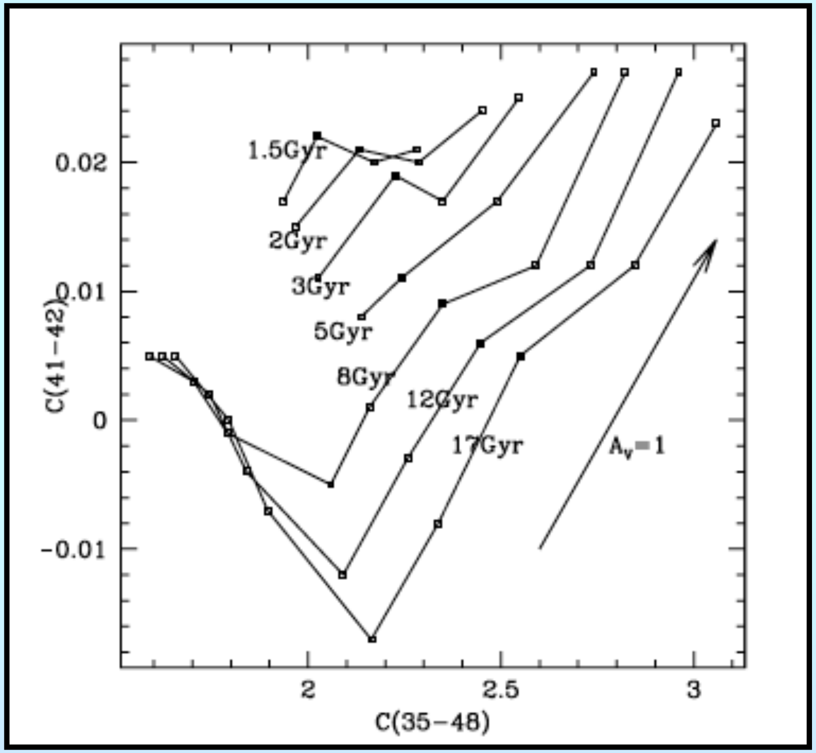


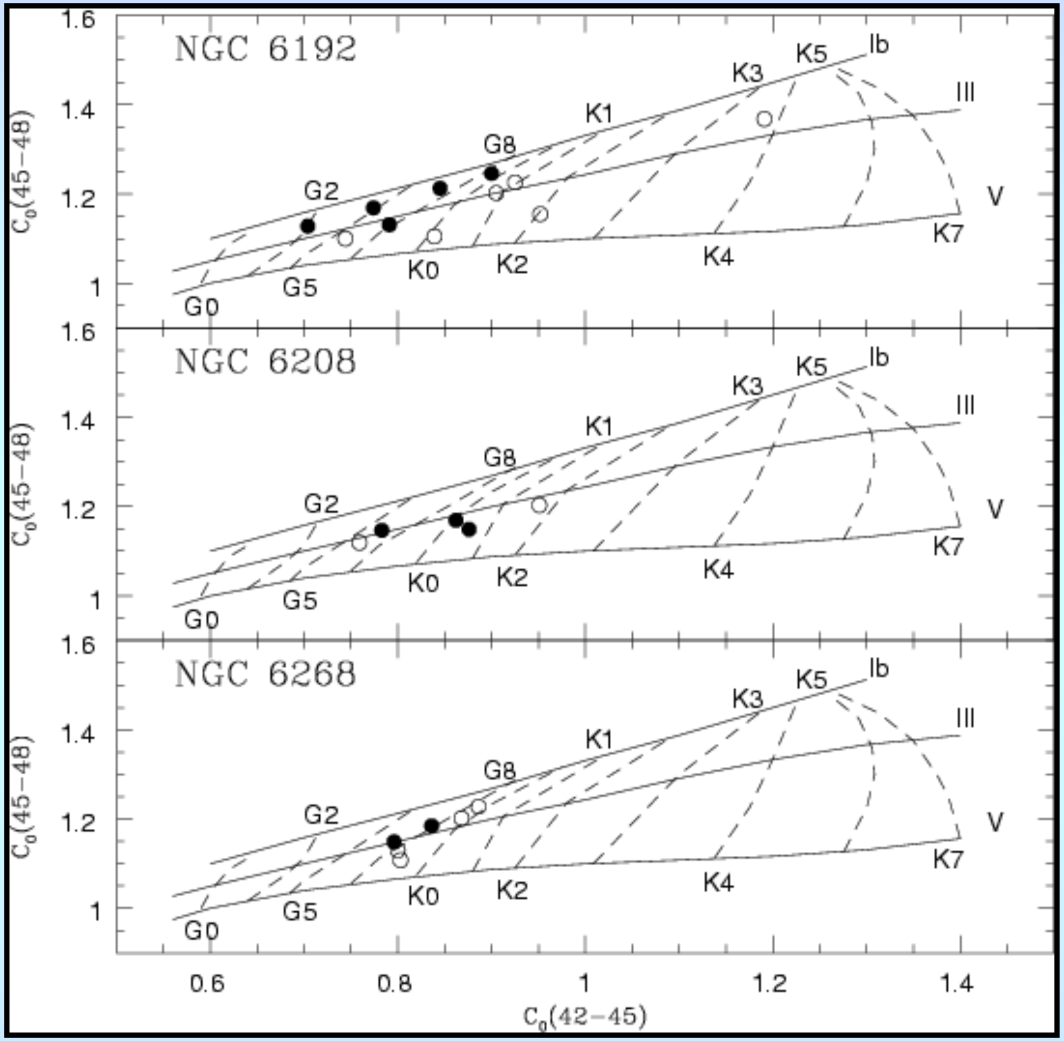


Filter	λ_{eff}	FWHM
35	3500 Å	390 Å
38	3800 Å	330 Å
41	4150 Å	75 Å
42	4250 Å	75 Å
45	4500 Å	75 Å
48	4800 Å	190 Å

DDO System

DDO indices are most effective for K-type giant stars.





Washington System

[Canterna 1976, AJ, 81, 228]

[Geisler 1990, PASP, 102, 344]

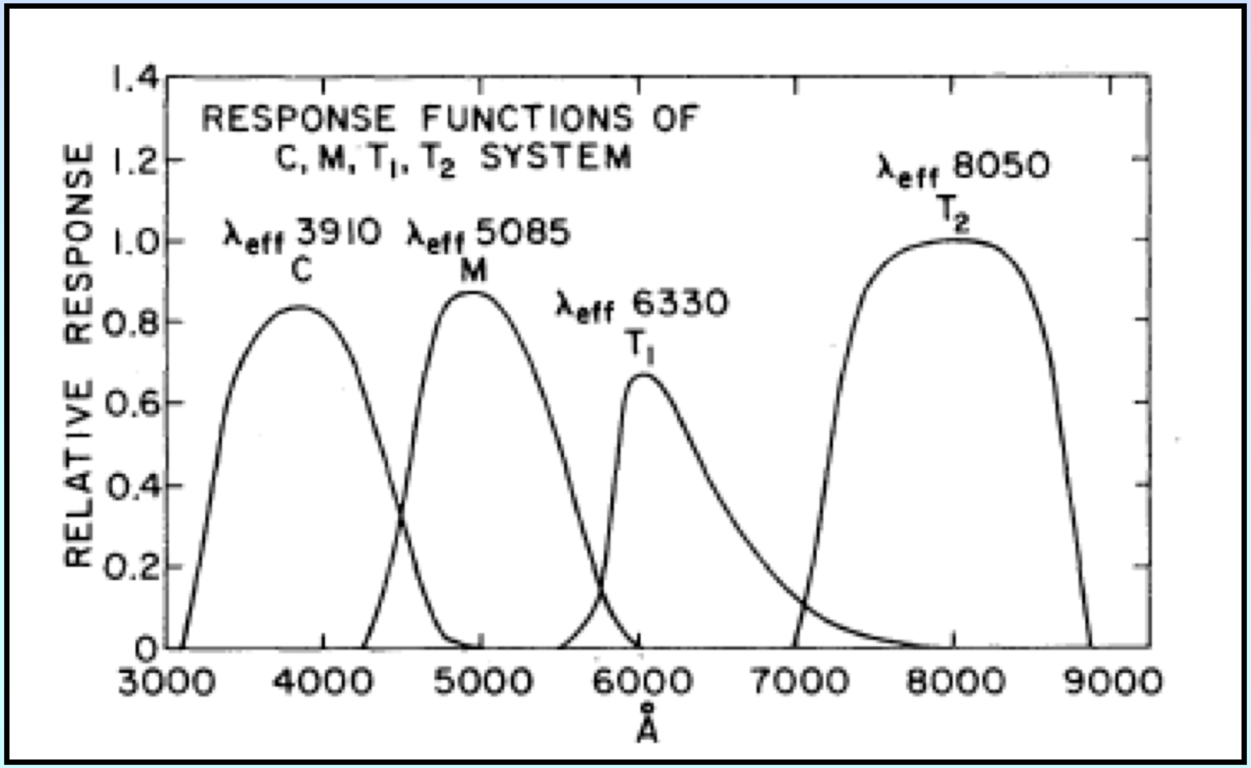
[Bessell 2001, PASP, 113, 66]

This is a wide-bandpass system designed to be sensitive to metallicity and age differences of old star clusters.

Advantage: Defined with astrophysics (of cool stars) in mind

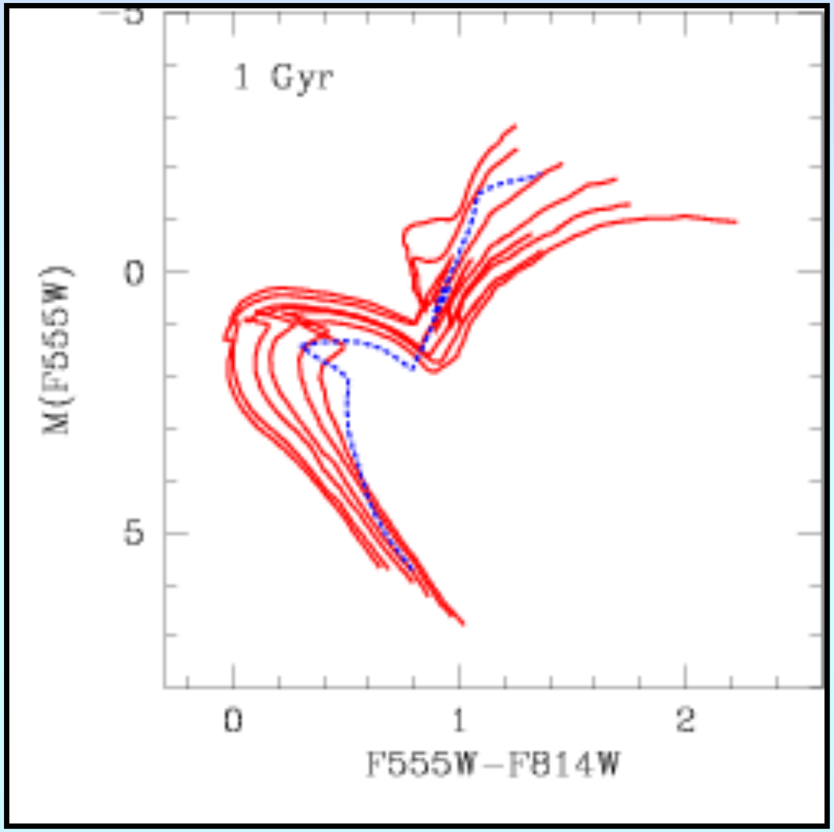
Disadvantage: Somewhat specialized; not used for many other programs.

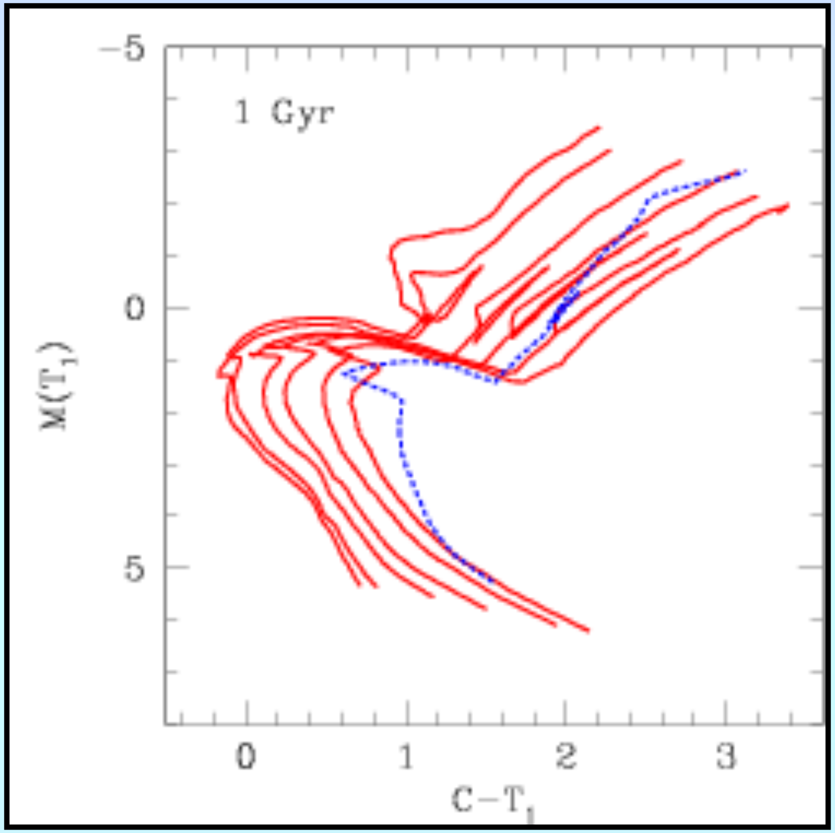
Washington System



Filter	λ_{eff}	FWHM
C	3910 Å	1100 Å
M	5085 Å	1050 Å
T_1	6330 Å	800 Å
T_2	7885 Å	1400 Å

Washington System





Although the Washington system is a broadband system, it has more sensitivity to stellar temperature than systems such as Johnson UBV, or the Space Telescope broadband filters.

Sloan System

[Thuan & Gunn 1976, PASP, 88, 543]

[Wade et al. 1979, PASP, 91, 35]

[Schneider, Gunn, & Hoessel 1983, ApJ, 264, 337]

[Fukugita et al. 1996, AJ, 111, 1748]

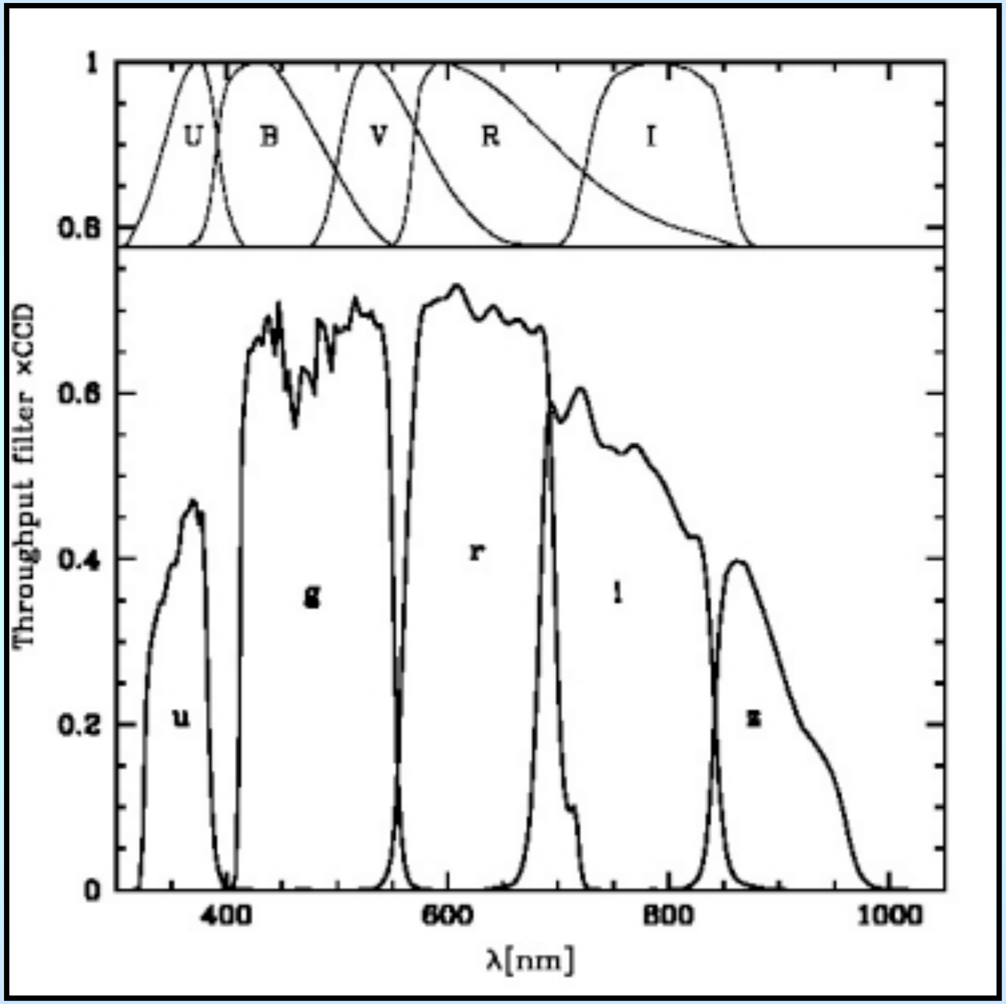
The SDSS system evolved from the Thuan-Gunn system, which has the star BD+17 4708 as its fundamental standard. Its wide bandpasses and high-throughput filters are optimized for faint objects.

Advantage: Defined for high-throughput, with some thought to (mostly extragalactic) astrophysical problems. Each bandpass is approximately the same width. Lots of data from the Sloan Digital Sky Survey (SDSS).

Disadvantage: Wide bandpasses result in ill-defined effective wavelengths.

Sloan System

Filter	λ_{eff}	FWHM
u	3500 Å	600 Å
g	4800 Å	1400 Å
r	6250 Å	1400 Å
i	7700 Å	1500 Å
z	9100 Å	1200 Å
y	12000 Å	1200 Å



Absolute versus Apparent Magnitudes

Strictly speaking, the magnitude definitions described above are *apparent* magnitudes, and they describe the relative fluxes observed for objects in the sky via

$$m = -2.5 \log \int S(\nu) F(\nu)\, d\nu + C$$

To describe the relative intrinsic luminosities of objects, one can use *absolute* magnitude (M). Absolute magnitude is the apparent magnitude an object would have if it were at a distance d = 10 pc. Absolute magnitude is therefore related to apparent magnitude by

$$m - M = 5 \log(d/10) = 5 \log d - 5$$

where d is in parsecs. ($m - M$) is called the distance modulus.

Absolute Magnitude versus Luminosity

Sometimes, one wants to convert absolute magnitude to solar luminosities. This requires knowing the apparent magnitude of the Sun in the given filter. This is extremely difficult to know!!!

Here are some *estimates* for the conversion between absolute magnitude and solar luminosity. The absolute magnitude of a star in filter X is related to its absolute luminosity (in solar units) by

Filter	λ_c	*C*	Flux @ m=0 (Jy)
U	3600 Å	5.61	1810
B	4400 Å	5.48	4260
V	5500 Å	4.83	3640
R	6400 Å	4.42	3080
I	7900 Å	4.08	2550
J	1.26 μm	3.64	1600
H	1.60 μm	3.32	1080
K	2.22 μm	3.28	670
u	3500 Å	6.55	3680
g	5200 Å	5.12	3730
r	6700 Å	4.68	4490
i	7900 Å	4.57	4760
z	9100 Å	4.60	4810

(1 Jy = 10^{-23} ergs/cm^2/s/Hz)

$$M = -2.5 \log \int S(\nu) L(\nu)\, d\nu + C \Rightarrow M_X = -2.5 \log L_X + C$$